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Cooperative System to Improve Safety at Controlled Urban Intersections

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ABSTRACT

In 2013 about 68.6% of all recorded crashes in Germany happened in urban areas. 32.8% of these crashes, which corresponds to 65,545 cases, were collisions with a vehicle turning or crossing. New communication technologies and powerful sensing systems have facilitated new technological possibilities in the field of ITS, which serve to improve traffic safety and efficiency in the urban area and to reduce these high numbers of crashes. Over the years a huge amount of research projects has investigated these new technological capabilities. Using the data vehicles transmit via vehicle-to-infrastructure communication on approaching an intersection, the Intelligent Cooperative Intersection Safety System – IRIS was developed as well.

The IRIS-System can reproduce and to predict traffic situations and to create a ‘bird’s eye view’ of the intersection based on precise position information provided by the vehicles, information on the control status of the traffic light controller and a detailed digital map. IRIS estimates the maneuver, predicts the future trajectory of the vehicles and the presence of vulnerable road users. Subsequently, IRIS uses this information to assess the evolving situation and to identify safety critical situations before they occur. Based on this threat assessment the system then decides whether to generate an appropriate warning message and to transmit it to the vehicle at risk.

The core of the IRIS-System is the maneuver estimation based on predefined reference tracks and a computation of the maneuvers’ probability of occurrence. The prediction of the trajectories follows these reference tracks and the concept of resistance points. The resistance points are used to model interdependencies between the vehicle and its driving environment. For assessing the threat of the evolving situation, IRIS computes the average required deceleration needed to get in line with the required speed. According to the value of the average required deceleration a safety or a critical warning is issued to the driver.

The IRIS-System has been tested extensively using artificially generated data. The results of the estimation of maneuvers, prediction of trajectories and the threat assessment are examined by means of different scenarios and different parameter settings. The capability of the IRIS-System was further demonstrated in a real driving environment at an intersection in the City of Dortmund. In 92% of the tests, the IRIS-System could interpret the evolving situation at the intersection correctly. Nevertheless, in 8% of the tests in Dortmund, technical shortcomings such as lost connection to the traffic light controller prevented correct interpretations.

Through the tests in the laboratory and at the real intersection the concept of the IRIS-System has been proved. Nevertheless, further effort is required to make the whole system more reliable. But a glimpse into the future of driving and intelligence at the infrastructure could be made.

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1 Preface

This chapter contains the introduction to the topic of the thesis. It describes the addressed problem and the hypotheses of the work. Furthermore, it scratches the basic idea and the scope of the work. The chapter closes with an outline of the dissertation implicating the methodology followed throughout the research.

1.1 Problem Definition and Hypotheses

In urban areas, Intelligent Transport Systems (ITS) are used for managing the traffic flow in dense networks of streets and roads. These systems should deal with a variety of road users such as car drivers, public transport, cyclists and pedestrians. Sensitive points in the urban area are intersections. Traffic signals are the main means of controlling traffic at these sensitive points. Alongside consecutive traffic signals, green waves are often established between intersections on main roads. The traffic signals themselves control various traffic streams to protect different road users from each other. This strategy only works well as long as everybody obeys the traffic rules. However, statistics show there are still several accidents which occur at urban intersections.

As per the 2013 report by the German Federal Statistical Office [GERMAN FEDERAL STATISTICAL OFFICE, 2014], the police recorded over 2.4 million accidents in Germany and 1.75 of these accidents occurred in urban areas. In 199,650 of these accidents people were injured and 977 people even were killed. 32.8% of the accidents with personal injury (65,545) were collisions with another vehicle turning or crossing. This was the most frequent kind of accident followed by 29,969 collisions of waiting or leading vehicles and 27,426 collisions of a vehicle and a pedestrian. While approaching controlled urban intersections and performing some of the actions listed above, the driver needs to pay attention to traffic lights, cyclists, pedestrians and even oncoming other vehicles. Therefore, the safe crossing at an intersection is not an easy task, even if the intersection is a controlled one.

Emerging technological possibilities in the field of ITS utilizing new communication technologies and powerful sensing systems provide opportunities to exchange valuable data from the vehicles to the roadside equipment and vice versa. The research question of this work is to verify the general hypothesis, that it is possible to use this exchange of data among the vehicles and the roadside equipment for addressing dangerous driving maneuvers at urban intersections and herewith improving traffic safety.

The idea was to design and establish a test system at a real intersection, using Vehicle-to-Infrastructure communication and the data exchange coming along with this technique. At the test intersection, driving maneuvers are assessed from a `birds-eye-view' and a waring is issued to the vehicle driver in case of danger.

The more detailed research questions arising from that idea and therefore the hypotheses, which are needed to be verified, are:

- It is possible to design a system, which is able to monitor and asses the driving maneuvers at an urban intersection. That means in detail to verify if it is possible to estimate the vehicles maneuver at the intersection, to predict the trajectory of the vehicle into the future and finally to assess the situation and trigger the transmission of a warning to the driver being in danger.
- It is possible to proof the system design and the processing steps in laboratory conditions and at a real urban intersection. That means to verify whether the maneuver estimation, trajectory prediction and the threat assessment are suitable for mitigating or preventing dangerous situations at urban controlled intersections.

1.2 Basic Idea and Scope

This thesis proposes a methodology for estimating the road users' maneuvers and for predicting their trajectories at an urban intersection. This estimation is a component for a system making accident-prone junctions safer using newly emerging cooperative systems. According to GRUNDEL ET AL. [2007] a cooperative system 1) consists of more than one entity, 2) the entities have behaviors that influence the decision space, 3) entities share at least one common objective, and 4) entities share information whether actively or passively. Using Vehicle-to-Infrastructure communication, a cooperative system can be established at intersections. The basic idea is that the system installed at the roadside monitors the whole intersection from a 'birds-eye-view'. This is possible by combining information provided by vehicles and by roadside systems. The information recorded about the vehicle includes its position and speed. This information is transmitted to the roadside via wireless communication. Furthermore, the detectors and sensors at the intersection provide information about passing vehicles and vulnerable road users near accident-prone locations. This bundle of information needs to be consolidated, predicted and assessed by the installed system at the intersection. This provides the possibility to identify safety-critical situations before they occur and to warn the affected road users.

To assist the driver at an urban intersection the proposed system addresses three scenarios:

1) the first scenario is approaching vehicles in danger of violating a red light at an intersection,
2) the second is vehicles turning right whilst a vulnerable road user is crossing the right approach of the intersection, and
3) the third scenario is vehicles turning left, which need to give way to oncoming traffic in case the turning is not protected by a separate green light.

The work of ROESSLER ET AL. [2005] gives evident that misinterpretation, obstructed view and inattention of driver are the reasons leading to crashes in these scenarios (for more details see paragraph 2.3). Therefore, and particularly because these scenarios represent the common maneuvers while passing an intersection, they have been selected. Furthermore, the selection was based on the seriousness of the situations - accidents involving vulnerable road users, for instance, often lead to serious injuries. Another reason, however, is the increasing complexity of the situation. As an appropriate approach for the design of this system the analysis starts from the less difficult prediction of movement of a single vehicle up to the very challenging prediction of complex scenarios involving cyclists and vehicles.

While elaborating the system, a variety of demanding tasks needs to be addressed. The first challenge is to match and align all the information about one object originating from different sources. For example, a vehicle transmits its position by itself, whereas a sensor tracks the vehicle, too. It needs to be determined whether both bits of information are related to the same object and, if this is the case, how the information can be consolidated. This procedure is called *object matching*. In the second step, the possible maneuvers and trajectories of the tracked objects need to be estimated and predicted. A methodology which enables the system to assess the evolving situation needs to be investigated. The last step of the main process chain is the assessment of the situation. Based on the predicted scenario, a decision needs to be drawn as to whether it is necessary to warn the road users or not. This is a very challenging task. If the system does not issue a warning, an accident might occur. However, if the system warns unreasonably, the road user will lose confidence in the system. Both events ought to be avoided.

The core of the thesis is the discussion and presentation of the method developed for estimating road users' maneuvers, predicting their trajectories and assessing the threat of the evolving situation at intersections. Object matching will only be mentioned briefly. The reason for this is that during the test at the real test site only information from sensors scanning a certain type of objects was available. That means no object matching was necessary. Another reason is that during the first step of installing cooperative systems, object matching will not play a major roll. This is because information about the same object sourcing from different sensors might only be available in a second generation of cooperative systems, for example in cases where vehicles might transmit not only information about themselves but also data about vehicles in their vicinity. Therefore, the thesis will not take object matching into detailed account, although this topic is important to investigated, too.

The thesis presents the methodology used to solve the above-mentioned problems in terms of finding appropriate solutions and algorithms. The thesis does not elaborate on topics such as software engineering, integration of different subsystems or communication aspects. Furthermore, the focus is clearly set on the algorithms running at the ITS roadside station (IRS), which is linked to the traffic light controller (TLC). The systems installed in the vehicles are mentioned, but not explained in detail.

1.3 Methodology and Outline of this Dissertation

The outline of the dissertation presents also an overview on the methodology which was accomplished.

Chapter 1: The preface at the beginning of the thesis introduces the topic and lists the research questions and hypotheses. Furthermore, the used methodology of the work is presented.

Chapter 2: To introduce the reader to the topic of the cooperative systems, the second chapter provides an outline of Intelligent Transport Systems (ITS) and of the concept of Cooperative Intelligent Transport Systems (C-ITS) as a part of ITS. As the thesis is focusing on urban intersections, the author provides a close look on crash statistics. This allows identifying the driving maneuvers, which will be supported by the system. In addition to that, an overview of different concepts for increasing safety at intersections is presented.

Chapter 3: This section outlines the concept of the Intelligent Cooperative Intersection Safety Application (IRIS), which is embedded in the architecture of the cooperative system developed by the European project SAFESPOT. The concept reflects the hypotheses stated in chapter 1. In addition, this section provides information on the data fusion model and its different levels. Based on these fusion levels the details of the IRIS-System are further elaborated.

The core of the thesis is the solution developed and investigated for predicting and assessing situations at intersections in terms of traffic safety. This is presented in the Chapter 4 to 6.

Chapter 4: As positioning of vehicles is an important element for monitoring and predicting trajectories, the fourth section starts with a literature review on positioning techniques. The main contribution is to estimate the future maneuver of the vehicle. To each driving possibility a certain probability is assigned to. This is the basis for the predicting the movement of the vehicle.

Chapter 5: Before explaining the concept of the vehicle movement approximation, the section reviews a bundle of other approaches on movement prediction. The resistance points are introduced for taking different dependencies of the approximated movement into account, such as a red light at the intersection. This chapter explains the prediction of the movement along a reference track. These tracks describe the most likely path a vehicle is going to take executing a certain maneuver at the intersection.

Chapter 6: After having computed a certain probability for a maneuver and an approximation of the movement of the vehicle, the evolving situation needs to be assessed. For this task, a closer look at traffic conflict techniques has been done. Based on this knowledge a methodology for assessing the situation is developed and a decision can be drawn whether it is necessary to issue a warning to the driver or not.

Chapter 7: The seventh chapter deals with the proof of concept of the proposed system. This proof of concept is split into tests executed in a virtual simulation laboratory and test runs at a real intersection. For the virtual test, artificially generated data by a microscopic traffic simulator is used. These data are fed into the system and the results of the maneuver estimation, movement prediction and threat assessment are compared under different setting. Having tested the system in the laboratory, the system can be established at a real intersection. The purpose of these tests was to integrate the IRIS-System in the real-world environment having installed laser scanners and equipped, cooperative vehicles running the tests. The chapter closes with some thoughts on open issues and the deployment of the IRIS-System.

Chapter 8: The thesis finishes with a summary of the findings and conclusion of the work.

2 Cooperative Systems in Transport

This paragraph introduces Intelligent Transport Systems (ITS) and gives a definition and a distinction of Cooperative Intelligent Transport Systems (C-ITS) in the world of ITS and driver assistance systems. A non-exhaustive overview on past and ongoing activities towards C-ITS is presented. This is followed by highlighting some C-ITS, especially the ones dealing with the urban driving environment. The paragraph continues with a short overview on the situation at today's intersections focusing on traffic safety and a review of the technological solutions and projects dealing with cooperative intelligent intersections to increase traffic safety.

2.1 ITS and Cooperative Intelligent Transport Systems

According to BUSCH [2008] traffic engineering faces a classical trade-off more than ever. On the one hand, conservation of the environment and dwindling resources need to be strongly considered when planning and operating today’s traffic and transport. On the other hand, mobility is an integral part of people’s daily life in terms of individual freedom and economic welfare. Therefore, mobility needs to be preserved and potentially increased.

Intelligent Transport Systems (ITS) play an important role in balancing out this trade-off. They are “*a technological instrument to implement measures of mobility and traffic management*.” [BUSCH, 2008]. Instead of building new roads, the improvement and the implementation of ITS with its applications such as adaptive traffic light control, variable message signs, temporally hard shoulder release and modern sensor technology, just to name a few, becomes more attractive. For a clearer understanding of the term ITS, it is worth looking at its definition. Even if there is a common understanding of ITS, a unique definition is missing. The most comprehensive one - in the Author’s point of view - is the one provided by the Intelligent Transport System Education Network:

"ITS integrate telecommunications, electronics and information technologies [...] with transport engineering to plan, design, operate, maintain and manage transport systems. This integration aims to improve safety, security, quality and efficiency of the transport systems for passengers and freight, optimizing the use of natural resources and respecting the environment. To achieve such aims, ITS require procedures, systems and devices to allow the collection, communication, analysis and distribution of information and data among moving subjects, the transport infrastructure and information technology applications.” [ITS-EDUNET, 2009].

According to this definition, ITS aim to improve traffic safety and efficiency with respect to the environment. This is achieved by applying a bundle of different methods and applications such as Urban Traffic Control, Dynamic Speed Adaptation, Ramp Metering, Public Transport Information, Route Guidance and Navigation, for example. In [MILES ET AL., 2004] the reader will find a comprehensive overview on today’s applications.

While thinking about ITS, another important area of research and development needs to be mentioned: Vehicles are also getting more and more intelligent using **Advanced Driver Assistance Systems (ADAS)**. Designing new ITS applications, the ADAS need to be taken into consideration as the capabilities of vehicles and the drivers' behavior changes. Referring to GELAU ET AL. [2012] ADAS are electronic systems onboard of vehicles that serve to support drivers in controlling their vehicle. The aim of these systems is to reduce the gap between the requirements of the traffic situation and the performance capability of the driver. Therefore, ADAS follow two main tasks. Firstly, they increase the time window for planning and executing the next driving task using warnings or recommendations. Secondly, ADAS assist the driver in getting back lost control of the vehicle. Some of the well-known examples of ADAS are Adaptive Cruise Control (ACC), Anti-lock Braking System (ABS), Electronic Stability Control (ESC), and Traction Control System (TCS). These systems rely fully on the information which is available on board of the vehicle gathered by inertial sensing devices, as well as by sensing devices recording the vehicle's surrounding; the driver is not actively involved. Thus, they are also labeled with the adjective “autonomous”.

Predominantly, the progress in communication, position and data processing technologies have led to a new kind of Intelligent Transport Systems, the **Cooperative Intelligent Transport Systems (C-ITS)**, Cooperative Mobility Systems or Cooperative Systems. Below we will use the term C-ITS. The idea of C-ITS in transport and traffic is to make vehicles communicate with each other while driving, as well as to enable the infrastructure to talk to the vehicles and vice versa using communication capabilities. To understand cooperative systems, it makes sense to look at a universal definition of the term *cooperative systems*. GRUNDEL ET AL. [2007] provide a general definition of cooperative systems. He stated that cooperative systems have the following common features:

1) more than one entity,
2) the entities have behaviors that influence the decision space,
3) entities share at least one common objective, and
4) entities share information whether actively or passively.

Transferred to the world of ITS in the transport engineering terminology, a cooperative system consists of entities which are the road users such as car drivers, cyclists and pedestrians as well as different entities of the infrastructure, such as traffic lights. The behavior of these entities influences the decision space such as cars moving along the road, changing lanes and VMS displaying certain messages. The entities have common objectives, too. If we understand the entity as an ITS user such as road users or operators in the traffic manage center, we can say that they share the common objective of a safe and efficient travel by using a minimum of energy, exhausting a minimum of emissions and having a certain level of comfort.

The first three features of cooperative systems according to GRUNDEL'S general definition also apply to conventional Intelligent Transport Systems, as we know them today. Nevertheless, to become a cooperative system, the different entities of the system need to share information, whether actively or passively. Look at the example of static traffic signs. We gather information from all the traffic signs we are passing by. However, this exchange of information is just one-way, from the sign to the driver. The driver might react on this piece of information, but the sign itself will never change its behavior. Even though todays' systems may allow an active detection of traffic signs by on board cameras such as described in [XIAOHUI ET AL., 2007] or the transmission of the content of the traffic sign via radio-frequency identification (RFID) technology, it cannot be viewed as a Cooperative System. The crucial point is that the information transmitted is not shared among these entities. One could say that the RFID reader emits radio waves, which activate the transponder. The RFID-equipped traffic sign does receive and use the information of the car passing by and the car is able to receive this information. Therefore, there is an exchange of information but the behavior of the traffic sign will never change because of that. This means that the traffic sign does not care whether the driver considers the information and there is no change in the behavior of the traffic sign while a vehicle is passing by, too.

Another example is traffic light control considering traffic situations. The control of traffic lights is changed because of information gathered from vehicles passing by or waiting in front of the lights. Based on GUNDEL'S definition, this is a cooperative system: there is more than one entity (1), their behavior influences the decision space (2), there is a common objective (3) - traffic efficiency and safety - and finally there is an exchange and common use of information (4) by detection systems and the visualization of the control status. These kinds of systems react to the current or evolving situation of the traffic and are known as traffic adaptive systems; we could also name them cooperative systems of the first stage. In the author's and general understanding, sharing of information or data respectively should take place by means of wireless communication technology to be in contrast to traffic adaptive systems. *"Co-operative systems are based on the real-time transfer of information from vehicle to vehicle, vehicle to infrastructure or infrastructure to infrastructure via radio interface"* to quote from [EUROPEAN COMMISSION, 2009]. GRUNDEL'S general definition needs to be limited at that point. Following the above argumentation and based on the definition of ITS, the definition of the ISO/CEN standardization organization according to SCHADE [02.10.2010] is the one which is used for the common understanding of C-ITS:

"Co-operative ITS is a subset of the overall ITS that communicates and shares information between ITS stations to give advice or facilitate actions with the objective of improving safety, sustainability, efficiency and comfort beyond the scope of stand-alone systems."

2.2 On the Road to Cooperative ITS

First Ideas and Implementation Projects

"*But these cars of 1960 and the highways on which they drive will have in them devices which will correct the faults of human beings as drivers. They will prevent the driver from committing* *errors. They will prevent his turning out into traffic except when he should. They will aid him in passing through intersections without slowing down or causing anyone else to do so and without endangering himself or others* [GEDDES, 1940]". "*Moreover, radio controllers would hold all motorists to within five miles per hour of the designated speed for their lane and the dangers created by the "Road Hog" and risky passing attempts would disappear*. [MARCHAND, 1992]"

These are the ideas of NORMAN BEL GEDDES, an American designer and visionary. His thoughts on future traffic and city life in the 1960ties, known as *Highways and Horizons* or '*Futurama*', were presented to the public in a General Motors pavilion during the New York's World Fair as early as 1939. As GEDDES shows, the vision of exchanging information among intelligent vehicles and an intelligent infrastructure by using communication technology is in fact not a new one.

Figure 2.1 Wolfsburger Welle reported by Zimdal [1983] according to [MENIG, 2012]

Nearly half a century later another car producer, the Volkswagenwerk AG together with Siemens AG presented "Autoscout" and the "Wolfsburger Welle". Using infrared (IR) beacons, which were mounted to traffic light poles along the test track in Wolfsburg, information about the traffic light was broadcasted to an onboard unit in the vehicle. The in-vehicle system displayed the driver where he/she is located, in relation to the green light of the traffic control. The Autoscout System provided guidance information such as convenient routes or information on congestion to the driver by using the same technology route [VOLKSWAGENWERK AG, 1983]. Figure 2.1 shows the in-car display and the IR transmitter at the traffic light pole and another one behind the windshield of the car.

This was an important step towards GEDDES' vision but still far from a true cooperative system and far from entering people's daily life. More and more cooperate research activities were necessary. Above all, the cooperation involving automobile manufacturers, transport industry, automotive suppliers and research institutes at a European level was the appropriate action to bundle the strength. The DRIVE I (1989-1991) and DRIVE II (1992-1994) programs with a variety of different projects fostered these activities. One important output was the agreement concerning the protocols for digital radio transmission of broadcasting traffic messages, established as the RDS/TMC standard. In addition, different task forces were built to work on dedicated short-range communication technologies for V2I communication [EUROPEAN COMMISSION, 2010]. In parallel to the framework program of the European Commission (EC), the leading automobile manufacturers of Europe launched the joint pre-competitive eight years research project PROMETHEUS (1987-1995) in 1987.

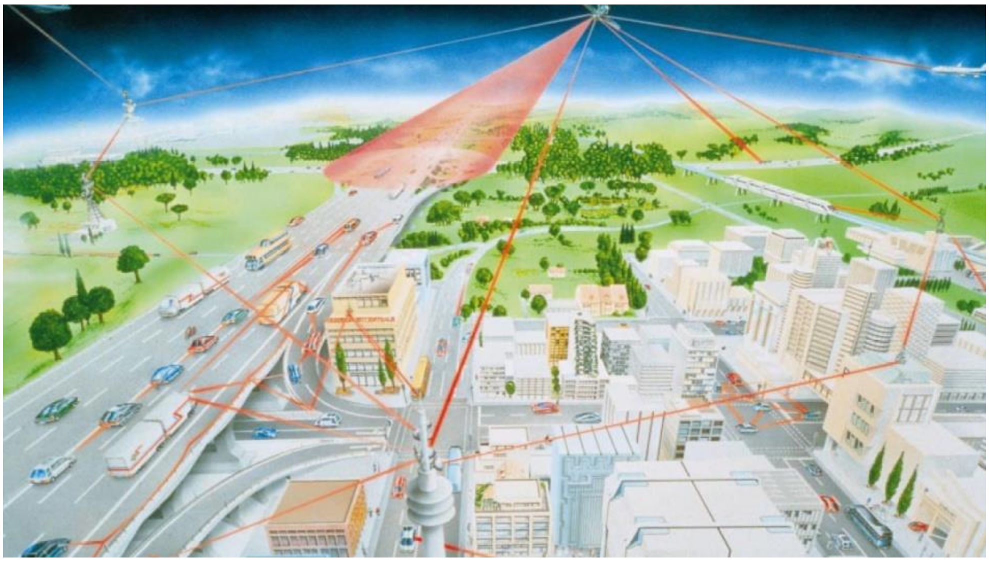

Figure 2.2 The vision of PROMETHEUS [BUSCH, 2013]

PROMETHEUS is an acronym for ''PROgraMme for European Traffic with Highest Efficiency and Unprecedented Safety'. According to [HELLAKER, 1990], the objectives of PROMETHEUS correspond to the three well-known goals of ITS; increasing traffic efficiency, improving traffic safety and reducing emission. The target to increase the driver’s comfort on his/her trip enriched these objectives. As stated by [BRAESS ET AL., 1995], the program was divided in four basic research projects: PRO-ART, which dealt with artificial intelligence, PRO-CHIP, which developed hardware for intelligent vehicles, PRO-COM, which proposed new standards for communications and PRO-GEN, which was responsible for traffic scenarios for assessment and the introduction of new systems and environmental communication. The three industrial projects PRO-CAR, which developed driver assistance, PRO-NET, which dealt with V2V communication and finally PRO-ROAD, which looked at V2I communication, completed the ambitious PROMETHEUS initiative. Figure 2.2 illustrates the vision of PROMETHEUS, which was quite close to GEDDES’ dreams. GILLAN [1989] highlighted the important cooperation between the DRIVE and the PROMETHEUS initiative, which mainly concerned the projects PRO-GEN and PRO-ROAD.

The functions for driver information and assistance that were investigated in PROMETHEUS were subdivided into vehicle autonomous functions such as obstacle detection, vehicle state deduction, autonomous intelligent cruise control and functions including the support of infrastructure, such as traffic flow control or intelligent intersection control. Not all of the envisioned functions could be developed successfully. BRAESS ET AL. [1995] report that due to technical constraints, especially in communication, legal aspects and driver acceptance, functions such as the intelligent intersection control could not be realized. However, the autonomous intelligent cruise control was resoundingly successful. A more detailed retrospective on PROMETHEUS can be found in BRAESS ET AL. [1995].

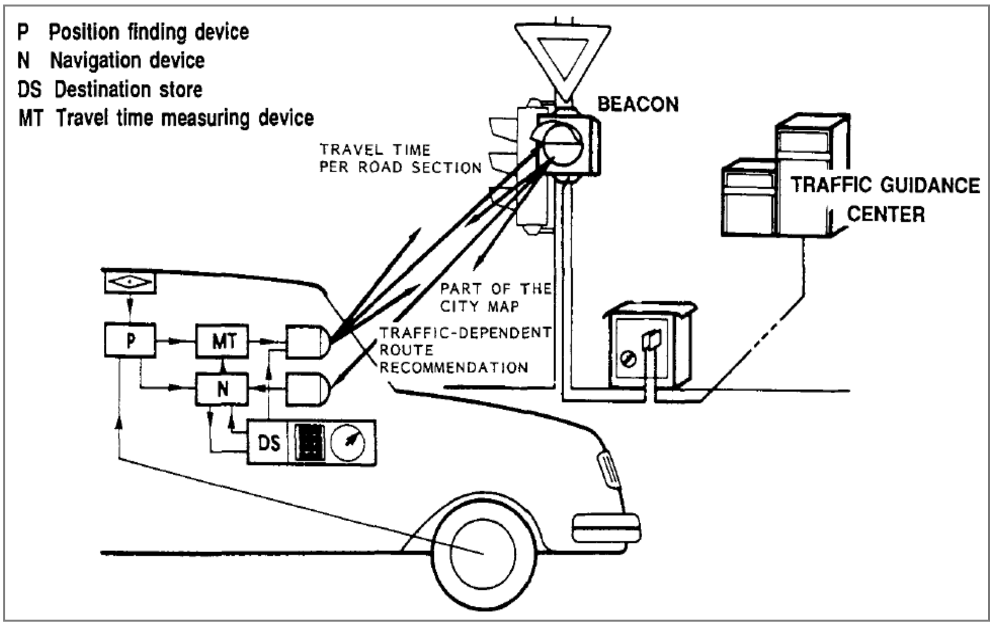

Figure 2.3 Operating principles of LISB [SPARMANN, 1989]

At this point, a first large field trial of an infrared (IR) beaconing system, the Leit- und Informationssystem Berlin – LISB project (1987-1995), for continuous updating of traffic and route guidance information should be mentioned, too. As SPARMANN [1989] reports, 250 intersections in the inner city of Berlin, 10 freeway intersections and 700 cars had been equipped for the successful one year field trail, which started in 1989. The traffic guidance center provided information on the traffic conditions and supplied route recommendations to all equipped vehicles. In addition, the vehicles transmitted the travel time of the road section they were driving on to the IR beacon. This information was further processed to draw an updated picture of the traffic situation for the traffic guidance center. Figure 2.3 depicts the principle of LISB during the initial period of Cooperative Intelligent Transport Systems in Europe.

Progress in Communication Technology and Standardization

Projects such as the afore-mentioned LISB showed great success at their time but were surpassed by modern navigation systems, developments in computational power and the possibilities offered by wireless communication technologies. KOSCH ET AL. [2009] report a variety of wireless communication technologies used for ITS in Europe. He categorizes them into

- **Short-range and ad hoc systems** including Dedicated Short Range Communications (DSRC), Wireless Local Area Network (WLAN) and Infrared (IR),
- **Cellular systems** such as Worldwide interoperability for Microwave Access (WiMAX), the Global System for Mobile communications und General Packet Radio Service (GSM/GPRS), the Universal Mobile Telecommunication System (UMTS) also known as 3G and in the future Long-Term-Evolution (LTE) which is also referred to as 4G, and
- **Digital broadcast systems** including Digital Audio Broadcasting (DAB) Digital Multimedia Broadcasting (DMB), Digital Video Broadcasting-Terrestrial (DVB-T), DVB-Handheld (DVB-H) and Global Position System (GPS).

For Cooperative Intelligent Transport Systems in the context of this thesis, ad hoc systems play the major role. Using WLAN, it is possible to setup vehicular ad hoc networks called VANETs. To operate a VANET the vehicles as well the infrastructure need to be equipped with radio interfaces and GPS receivers for gathering accurate times and positions. From the communication point of view, vehicle and infrastructure are the same at this basic level. The research on wireless vehicular communication brought up many standards ranging from protocols that apply to transponder equipment through to routing, addressing services, and interoperability protocols, as stated by ZEADALLY ET AL. [2010].

The U.S. Federal Communication Commission (FCC) took a first step towards VANETS in 1999. The FCC allocated 75 MHz bandwidth of the *“5.850-5.925 GHz band for a variety of Dedicated Short Range Communications (DSRC) uses, such as traffic light control, traffic monitoring, travelers' alerts, automatic toll collection, […]”* [FEDERAL COMMUNICATIONS COMMISSION, 1999]. According to KENNEY [2011] the word ‘dedicated’ refers to the allocation of the spectrum. The term ‘short range’ indicates that the communication takes place within a range of about some hundred meters. This is far shorter than cellular communication or WiMAX. HARTENSTEIN ET AL. [2010] got straight to the point when they wrote that this action is a kind of change in the game and fostered the research on ITS using DSRC. Furthermore, HARTENSTEIN reports that standard the IEEE 802.11a technology has been selected by a working group of American Society for Testing and Materials (ASTM) International as a foundation for the corresponding DSRC. As JIANG ET AL. [2008] state, the use of WLAN in a vehicular environment brings up new requirements, as vehicular safety communications applications cannot tolerate long connection establishment delays before being enabled to communicate with other vehicles or the infrastructure. Therefore, in 2004, the Institute of Electrical and Electronics Engineers (IEEE) started to work on the IEEE 802.11p standard considering these new requirements. Also in Europe, the EC dedicated the 30 MHz bandwidth of 5.875-5.905 GHz band to safety-related ITS applications on 5th August 2008, which improve road safety by increasing the amount of information about the environment, other vehicles and other road users that is available to the driver and the vehicle [COMMISSION DECISION of 5th August 2008 on the harmonized use of radio spectrum in the 5 875-5 905 MHz frequency band for safety-related applications of Intelligent Transport Systems (ITS), 2008].

However, allocation of the spectrum is only part of the work. Message sets and communication protocols need to be standardized. Such message sets form the common language whereby vehicles and infrastructure can understand each other. This refers mainly to the application layer of the communication stack. As ALEXANDER ET AL. [2011] point out that this dictionary determines - among others - the basic set of safety messages as well as messages necessary for the notification of an approaching emergency vehicle or road works or messages that allow communication with traffic lights. Furthermore, probe vehicle data messages have been defined as well as generic messages, which allow flexibility in the future for the creation of new applications. In the U.S., the Society of Automotive Engineers (SAE) is leading in this field and has created the SAE J2735 message set dictionary [U.S. DOT, 2009]. The IEEE 802.11p standard forms the communication basis for the IEEE 1609 family, referred to as Wireless Access in Vehicular Environments (WAVE). WAVE provides wireless access in vehicular environments considering communication protocols, networking services and security services among other things [UZCATEGUI ET AL., 2009].

In 2008, the European Commission published the Action Plan for the Deployment of Intelligent Transport Systems in Europe to foster the deployment of ITS. In 2009, this was followed by Mandate M/435 of the EC asking the European standardization organization ETSI, CEN and CENELEC to work closely together to achieve “a coherent set of standards, specifications and guidelines to support European Community wide implementation and deployment of Co-operative ITS systems” [Standardization Mandate addressed to CEN, CENELEC and ETSI, 2009]. ETSI defines a basic set of applications (traffic hazard warnings, collision risk warning, cooperative flexible lane change, to name just a few), which are considered as deployable within a three-year timeframe after the completion of their standardization. These message sets are divided into the Cooperative Awareness Messages (CAM) and the Decentralized Environmental Notification Message (DENM). The CAMs are distributed within the VANET and *“provide information of presence, positions as well as basic status of communicating ITS stations to neighboring ITS stations that are located within a single hop distance. All ITS stations shall be able to generate, send and receive CAMs, as long as they participate in V2X networks. By receiving CAMs, the ITS station is aware of other stations in its neighborhood area as well as their positions, movement, basic attributes and basic sensor information,”* as specified in [ETSI, Technical Specification TS 102 637-2]. The DEN Messages are mainly used to alert road users of detected events such as broken-down vehicles, traffic light violation or the end of a traffic jam [ETSI, Technical Specification TS 102 637-3]. In this standardization, not only European views are taken into account, but also the ideas and results from the SAE and bodies such as the Car to Car Communication Consortium[1] (C2C-CC) are considered as well as the final joint CEN/ETSI-Progress Report on Mandate M/453 [CEN ET AL., 2013] states. As a first result of the standardization effort ETIS and CEN announced the first release of

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[1] The CAR 2 CAR Communication Consortium is a non-profit industrial driven organisation initiated by European vehicle manufacturers supported by equipment suppliers, research organisations and other partners. It is dedicated to the objective of further increasing road traffic safety and efficiency by means of Cooperative Systems in Transport [C2C-CC, 2013]

standards referring to C-ITS in February 2014 [Dahmen-Lhuissier, 2014]. For further information on the standardization work the reader is referred to [iCarSupport, 2012], [ETSI, 2014] and [European Commission, 2012].

An important point in the development of ITS and C-ITS is the evolution of necessary technical components and the reduction in prices coming along with mass production. More people are able to afford these technologies, starting from smartphones, connected navigation systems and applications integrated in new vehicles. This development increases the data availability for computing and predicting the traffic situation in large road networks. This is a revolutionary fact in ITS and traffic engineering, too. The data available in some parts overrules classic traffic models. But this is beyond the scope of cooperative system as they are understood in this thesis.

Recent and Ongoing Activities in Europe

C-ITS are still under further development as technology continuously improves. This paragraph highlights some of the European initiatives. With the 5th to 7th European Research Framework Programs the EC has fostered and is still fostering this process in past and in future projects and the ensuing program Horizon 2020 is doing so, too. The European Project CarTalk2000 (2001-2004) focused on new driver assistance systems which were based upon communication between vehicles. The aim was on the one hand to develop new driver assistance systems and one the other to develop an ad-hoc radio network as a communication basis with the aim of preparing a future standard [Reichardt et al., 2002]. Moreover, Franz [2004] covers, amongst others, the French-German Inter-Vehicle Hazard Warning project (2001-2002), which aimed to broadcast warning messages on motorways to vehicles in a communication range of 1 km, the German FleetNet project (2000-2003), which had the aim of developing new algorithms and communication protocols for V2V applications using different communication media, the European CHAUFFEUR II (2000-2003) project, which improved the truck platooning capabilities of CHAUFFEUR I using new communication technologies and the German Network on Wheels (NoW) project (2004-2008) which had amongst others the objective to develop routing protocols and data security in ad-hoc networks with a focus on vehicles safety.

In 2004, the EC launched the 6th Framework PReVENT project (2004-2007). PReVENT’s goal was to develop, test and evaluate applications for increasing traffic safety, to advance in-vehicle sensors and V2V communication technologies and finally, to integrate them in dedicated demonstrator platforms. The project itself was split up into several subprojects (SPs) dealing e.g. with data fusion on board of the vehicle, driver support in the lateral control of vehicles and protection of road users through activation of vehicle safety systems right before an accident occurs. The SP Wireless Local Danger Warning (WILLWARN) aimed to develop a full safety V2V application (not only communication technology and protocols) that works reliably even when the system penetration rate is low in the beginning. The WILLWARN radios were also used in the PReVENT SP INTERSAFE to link traffic lights to the vehicles. The objective of INTERSAFE was to provide a basic intersection safety system to reduce and eventually avoid casualty accidents at intersections by the use of board sensors and communication technology [SCHULZE ET AL., 2008]. The work on INTERSAFE was continued in INTERSAFE 2 (2008-2011) and the safety application further elaborated by including infrastructure based sensors [ROESSLER, 2010].

At a European level, research continued in three subsequent projects: COOPERS, CVIS and SAFESPOT [AMSTERDAM RAI, 2010]. Within the project COOPERS (2006-2010), different wireless technologies were used to enhance traffic efficiency and safety on motorways. The focus of CVIS (2006-2010) was set on developing a basic communication and application framework for C-ITS and services for improving drivers' comfort and traffic efficiency in urban areas and on motorways. The aim of SAFESPOT (2006-2010) was to develop C-ITS for traffic safety using V2V and V2I data exchange balancing out the leverage of vehicles and infrastructure. The designed applications dealt with situations on motorways, on rural roads and within urban environments. Based on this work the three-year project eCoMove started funded by the European Commission as a part of the 7th Framework Program in 2010. The objective of eCoMove was to reduce the overall fuel consumed in traffic by 20 percent by using Cooperative Systems [VREESWIJK ET AL., 2010].

Research on C-ITS is promoted not only on a European level, but also on a national level, such as in Germany. In Germany, work in several nationally-founded projects including the project *AKTIV* (2006-2010) made it possible to gather experience in C-ITS by developing applications such as Virtual Traffic Guidance System, Cooperative Traffic Signal and Adaptive Navigation [AKTIV, 2011]. These activities are being continued in the UR:BAN research initiative (2012-2016), which is concerned with applications in urban areas and focuses on network wide aspects, urban main roads and single intersections in order to improve safety and reduce energy consumption. A further important issue in cooperative systems and wireless communication is the protection of data against misuse. The EC-founded projects such as SeVeCom (2006-2009) and PRECIOSA (2008-2010) were dealing with privacy and security issues [KUNG, 2009].

In all aforementioned projects, the core intention was to develop and test cooperative applications and to figure out the possibilities and limitations offered by wireless communication. However, these tests and demonstrations only included a small sample of cars and an even smaller number of equipped infrastructural devices. To gain knowledge about the impact and acceptance of C-ITS on a larger scale, data from so-called Field Operational Tests (FOT) comprising more test vehicles and running for a longer time, in combination with traffic and driver simulation studies, were necessary. In Europe, initiatives such as the field operational test support action FESTA (2007-2008) were heading in that direction - they produced guidelines for setting up FOTs [FESTA CONSORTIUM, 2008], and Pre-Drive (2008-2010), which acted as a preparation for the large scale FOT for cooperative systems that were being conducted in the DRIVE C2X project (2011-2013). In DRIVE C2X, the FESTA handbook on FOTs has been implemented. [STAHLMANN ET AL., 2011]. Projects on a national level include the Dutch SPITS project [SPITS, 2011]. SPITS examined data from large scale field tests to analyze shock wave damping on motorways, among others. In the French project SCORE@F an FOT was also set up [SCORE@F, 2013]. In Germany, the sim^{TD} project (2008-2012) followed the same path. The sim^{TD} project aimed at demonstrating and evaluating the effectiveness of applications dealing with traffic management, hazard warnings and commercial services in real life conditions that exceed the demonstrator capabilities. The overall goal was to gain information on which deployment decisions for cooperative systems can be based [WEIß, 2010]. The EC-founded support initiative FOT-Net (2011-2013) provided a strategic networking platform for exchanging experiences in setting up, running and assessing FOTs [FOT-Net, 2011]. In addition, the support actions carried out in the projects COMeSaftey (2006-2009) and COMeSaftey2 (2011-2013) have to be mentioned. These initiatives served to support the realization and a possible deployment of cooperative systems focusing on communication-based active safety systems [COMeSafety2, 2013].

But not only the research projects and FOTs were necessary steps for C-ITS to come into being. As mentioned before, the European Commission published the ITS Action Plan [Action Plan for the Deployment of Intelligent Transport Systems in Europe, 2008] in 2008 to foster the deployment of ITS in Europe. The ITS Action Plan was followed by the ITS Directive of the European Parliament and of the Council [Directive on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport, 2010]. This authoritative directive set the scene for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport. The directive came into effect on August 26, 2010 and needed to become national law within 18 months. Consequently, Germany adopted the national law “Intelligente Verkehrssysteme Gesetz – IVSG”, which provided a legal and binding framework for the introduction of new ITS. Furthermore, Germany is developing the national IVS-Aktionsplan Straße, which is to support the deployment of ITS in Germany by 2020 [BMVI, 2014].

This overview of the formation and development of C-ITS in Europe shows that we have come a long way from the early days starting with the PROMETHEUS project. A lot of effort has been put into specification, development and testing of applications as well the standardization of data formats and interfaces. The Cooperative ITS Corridor is the latest ambitious activity in the field of C-ITS. The Netherlands, Germany and Austria are currently setting up a motorway corridor to establish the first permanent set of C-ITS applications to run across Europe. The focus is mainly on roadwork warning, as this is one of the less complex but promising applications.

Activities in the United States and Japan

To complete the picture on C-ITS two other pioneer countries should be mentioned, the United States and Japan. KARAGIANNIS [2011], ZEADALLY [2010] and CREGGER [2014] present a good overview on the activities and projects in these countries. The following is mainly based on their work.

In the U.S. the research on ITS started around the same time as in Europe. According to SHLADOVER [2007] the California Partners for Advanced Transit and Highways (PATH) Program founded in 1986 was the first research program in North America that focused on Intelligent Transport Systems. One of the success stories of PATH is the platooning application. The experimental vehicles were equipped with a communication unit amongst others to exchange time stamp, speed and acceleration to perform an automatic longitudinal control to drive in a close-formation platoon [CHANG ET AL., 1991]. Further on SHLADOVER reports, that in 1989 the Mobility 2000 initiative was founded which became the Intelligent Vehicle Highway Society (IVHS) America in 1991. The term IVHS that also stands for Intelligent Vehicle Highway Systems was changed to ITS in 1993 *“in order to emphasize the broader multimodal applications of the systems. It was important that this be not just seen as a program for ‘vehicle industry’ and ‘highway’ interests but that it address the needs of the transportation system as a whole”* [SHLADOVER, 2007]. In addition, JURGEN’S [1991] article “Smart cars and highways go global” expresses by its name this trend.

A major step forward was done though the Intelligent Vehicle Initiative (IVI) (1998-2004). The goal of the IVI program was to reduce the severity of crashes or prevent them, through technologies that help drivers to avoid hazardous mistakes as ZEADALLY ET AL. [2010] report. The objectives of the program were to develop assisting systems to prevent driver distraction and accelerate the development and deployment of crash avoidance systems.

The Vehicle Safety Communications (VSC) consortium set its focus on assessing how previously identified critical safety scenarios can be improved by the use of Dedicated Short Range Communications (DSRC) along with positioning systems. The activities of the VSC already started in 2002 and recently finished its third phase, the VSC-3 (2010-2014). The VCS-3 conducted field trials under the U.S.DOT Safety Pilot Program. This activity studies scalability aspects of vehicle safety communications that will preserve the performance of vehicle safety applications in both congested as well as uncongested communication environments. According to CREGGER ET AL. [2014] the tests involved 2,836 vehicles equipped with vehicle-to-vehicle (V2V) communication devices using 5.9 Gigahertz (GHz) DSRC. The vehicles, comprising cars, trucks, commercial vehicles, and transit vehicles, transmit information, such as location, direction, speed, and other vehicle data, during testing.

The Vehicle Infrastructure Integration (VII) Consortium (2004-2009) supports the development of C-ITS in coordinating between key automobile manufacturers, IT suppliers, U.S. Federal and state transportation departments, and professional associations. The VII test environment covers 50 square kilometers near Detroit, USA and is used to test a variety of prototype VII applications. According to ZEADALLY ET AL. [2010] the specific applications include e.g. warning drivers of unsafe conditions and imminent collisions, warning drivers being about to leave the road accidentally, providing real-time information to system operators concerning congestion, weather conditions, and other potentially hazardous incidents and providing operators with real-time information on corridor capacity.

However, not only in Europe and the U.S. the ideas of (C-)ITS were promoted and the activities on the issue were bundled and coordinated. According to NAKAHARA [1997], in the late 70’s in Japan the Comprehensive Automobile Control System (CACS) project based on IR beacon communication has been completed successfully. The Road Automobile Communication System (RACS) project conducted comprehensive testes on bi-directional communication between vehicles and the roadside. In 1996, the Vehicle Information Communication System (VICS) started supplying real time traffic information through IR beacons, radio wave beacons and radio broadcast to the drivers.

Furthermore, it is worth to mention the Advanced Safety Vehicle (ASV) project, that started in 1991 with the aim to use intelligent communication technology for improving safety and was followed by (ASV-2) (1996-2000), (ASV-3) (2001-2005) and (ASV-4) (2005-2007) [WANI, 2006]. The trials of the ASV-project series focused on active and passive safety. In the active safety trial, systems were tested that addressed inattention and driver errors. These relate to systems for drowsiness warning, vision enhancement, navigation, automatic collision avoidance and lane departure warning. The passive systems included impact absorption systems, occupant protection systems, pedestrian protection systems and door lock sensing systems as ZEADALLY ET AL. [2010] reports. According to FUJIOKA [2002], in Japan the Demo 2000 was undertaken right before the change in the 21st century. The core technology of the cooperative driving system presented to the public in the Demo 2000 was an inter-vehicle communication technology. Each vehicle was equipped with laser radar for the measurement of distance, obstacles, and liquid crystal displays for visualizing vehicle communication.

The SMARTWAY project was launched 2007 to create a road system that could exchange information among cars, drivers and pedestrians using DSRC. Further on, CREGGER ET AL. [2014] report that it “was originally a field test of various road warning applications, such as merge assist, curve warning, congestion warning, and weather information. In the original test, sensors were placed in vehicles which received input from the applications on the road. In 2008, additional field tests were conducted, with the intent of leaving the infrastructure in place as it was the case with the 2007 test. In 2009, these test beds were expanded and made available to the public. By 2010, around 1,600 ITS Spot units were installed, mostly located on expressways.” Since November 2010, several other automakers and navigation system manufacturers have released systems that interact with ITS Spot units. About 10 years after the Demo 2000, the ITS-Safety 2010, a large-scale verification testing project for Driving Safety Support System (DSSS) (see page 26), ASV, and SMARTWAY, was launched. ITS-Safety 2010 had the goal of achieving practical application of vehicle-infrastructure cooperative systems [CREGGER ET AL., 2014].

Closing this section, it is important to mention the following: As cars are sold around the world the activities in finding standards for C-ITS needs to be harmonized on a global context. Therefore, the EC and the U.S. Department of Transport (DOT) singed on the 13th November 2009 an EU-U.S. Joint Declaration of Intent on Research Cooperation in Cooperative Systems. One outcome of this joint activity is the Harmonization Action Plan on Cooperative Systems, adopted on the 30th June 2011. It clearly states that the goal is to “support, wherever possible, global open standards to ensure interoperability of cooperative systems worldwide and to preclude the development and adoption of redundant standards [EU-US Cooperative Systems Standards Harmonization Action Plan (HAP), 2011].” Also with the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) the European Commission signed a Memorandum of Cooperation on "Cooperative Systems in the Field of Intelligent Transport Systems" on the 9th June 2011. In addition, tri-lateral EU-US-Japan negotiations took place already. For further information on the standardization work the reader is referred to [CEN ET AL., 2013], [ICARSUPPORT, 2012], [ETSI, 2011] and [EUROPEAN COMMISSION, 2012].

2.3 Traffic Safety at Today’s Intersections

Intersection applications in urban areas are much more complex and certainly not the first C-ITS applications to be deployed. Nevertheless, sooner or later this kind of applications will play an important role as well. This section provides an overview of the applications and systems dealing with intersection safety, with is still a challenge to cope with in C-ITS. Herewith, the section completes the review on C-ITS in general and assistance systems at intersection in special.

Intersections are the most critical spots in terms of traffic safety in urban areas. In 2013, German police recorded 199,650 accidents in urban areas. About 42% of these accidents occurred while turning or crossing at intersections, of which 55% lead to heavy material damage and 43% led to injured road users. In total 263 of the 977 people who lost their lives in urban traffic were killed because of misbehavior while crossing or turning [GERMAN FEDERAL STATISTICAL OFFICE, 2014]. The Federal Statistical Office reports further that the driver's age played a big role in those accidents. Inappropriate speed and distance to the vehicle in front are more commonly reasons for an accident caused by young drivers. Older drivers on the other hand tend more to overlook right of way or make mistakes while turning or crossing. This is an indicator that older drivers have difficulties in handling the complex situations at intersections. This could lead to an increasing problem in an aging society, especially in the urban environment. Assistance systems especially designed for the needs of a safe crossing of intersections might be a suitable solution to cope with this situation.

In 1999, data collection teams of the German Federal Highway Research Institute (BASt) and the German Research Association of Automotive Technology (FAT) started to record traffic accidents with at least one injured person in the greater areas of the cities Hannover and Dresden directly at the crash site and immediately after the accident occurred. The German In-Depth Accident Study (GIDAS) reports this collected data, which is about 2000 accidents a year. The circumstances of these accidents are then usually reconstructed and reported in detail. In contrary to the accident statistics freely available from the Germany Federal Statistical Office, the purchasable customized queries of the GIDAS-database lead to more details and combinations of variables [MEITINGER, 2008].

ROESSLER ET AL. [2005] did an analysis of intersection accidents listed in the GIDAS-database for red light violations, unprotected left turning and turning in or crossing at intersection. In total, they based their analysis on about 3,300 accidents at intersections. The flowing tables represent the results of this analysis, indicating the reason for each accident. These reasons are differentiated between misinterpretation, obstructed view and inattention. Furthermore, the researchers investigated whether there was any avoidance maneuver such as braking or steering and whether this attempt was successful or not. For red light violations 171 accidents could be analyzed, as indicated in Table 2.1. The main reason for those red-light violations was either that the driver did not pay enough attention or misinterpreted the signal. In 60% of the cases, braking was chosen as avoidance maneuver with a 41% success rate (Table 2.2). The drivers seemed to recognize the red light at a very late stage and tried to avoid a potential crash by braking. These facts suggest that a cue or warning approaching a red light might be helpful in these cases.

Kind of Mistake (n=171)		
Misinterpretation	**Obstructed View**	**Inattention**
31%	3%	30%

Table 2.1 Driver mistake assigned to red light violation [ROESSLER ET AL. 2005]

Avoidance Maneuver (n=165)			
Braking		**Steering**	
No Attempt	Unsuccessful attempt	No Attempt	Unsuccessful attempt
40%	59%	66%	30%

Table 2.2 Avoidance maneuver assigned to red light violation [ROESSLER ET AL. 2005]

Turning at or crossing an intersection controlled by traffic lights should be rather safe as the light is protecting conflicting traffic streams from each other. However, as ROESSLER ET AL. [2005] report, 148 of the 171 red light violations resulted in conflicts with other crossing vehicles. In the case of crossing without traffic lights, the drivers must estimate the gaps in-between the crossing traffic streams and choose a safe one. A possible reason for accidents could be a misjudging of the speed of other drivers, due to an obstructed view or the overestimation of the acceleration capacity of their own vehicle. Crossing an intersection is a quite demanding task, so some important conditions could be overlooked, which leads to the rather high rate of inattention (36%) as Table 2.3 states. Also braking is the mean of choice of drivers to avoid accidents, which is successful in 45% of the cases (Table 2.4). Steering maneuvers do not seem to be good options as there might be not enough time left to evade successfully.

Kind of Mistake (n=437)		
Misinterpretation	**Obstructed View**	**Inattention**
33%	23%	36%

Table 2.3 Driver mistake assigned to turning in or crossing [ROESSLER ET AL. 2005]

Avoidance Maneuver (n=437)			
Braking		**Steering**	
No Attempt	Unsuccessful attempt	No Attempt	Unsuccessful attempt
42%	55%	60%	31%

Table 2.4 Avoidance maneuver assigned to turning in or crossing [ROESSLER ET AL. 2005]

Kind of Mistake (n=437)		
Misinterpretation	**Obstructed View**	**Inattention**
38%	16%	5%

Table 2.5 Driver mistake assigned to unprotected left turn [ROESSLER ET AL. 2005]

Avoidance Maneuver (n=437)			
Braking		**Steering**	
No Attempt	Unsuccessful attempt	No Attempt	Unsuccessful attempt
51%	46%	63%	26%

Table 2.6 Avoidance maneuver assigned to unprotected left turn [ROESSLER ET AL. 2005]

The unprotected left turn can also happen at controlled intersections. In the case of the reported 437 accidents, it is not known whether the intersection was a controlled one or not (Table 2.5). ROESSLER ET AL. [2005] report that misinterpretation of the oncoming vehicles' speed, ambiguity of traffic control (oncoming traffic expected to stop for intersection clearance) and sun glare are common reasons for accidents in these situations. Table 2.6 shows, that in over 50% of the cases, the drivers did not initiate any avoidance maneuvers. This might be because they realized the dangerous situation far too late. An assistance system might be able to provide the drivers with the necessary time to react properly to avoid the crash.

Important to mention looking at accident statistics are the crashes having involved a car and a bicycle. GERSTENBERGER [2015] reports in his work, based on the German In-Depth Accident Study (GIDAS) undertaken in Hannover and Dresden, that 34.8% of all crashed having involved a car and a bicycle. This is 2,144 crashes of the total 6,162 crashes recorded at intersections from July 1999 to December 2011. These evidences the importance of protecting the bicycle riders in the urban environment and so does the IRIS-System, as described later.

2.4 Collision Avoidance Systems at Intersections

As the need for assisting drivers at intersections is not new to researches, the following chapter presents a short overview of some of the activities in the field of collision avoidance systems (CAS). In principle, there are two main categories of intersection safety systems: stand-alone and cooperative ones. The stand-alone systems collect information from their surrounding environment independently or have this information already integrated in there onboard navigation system in case of a vehicle system and draw appropriate conclusions. That means that only the infrastructure or only the vehicle is responsible for dealing with situations and for assisting the driver. Cooperative systems, on the other hand, exchange information and draw conclusions based on exchanged data. Four different collision avoidance systems are distinguished [MAGES, 2008]:

- Infrastructure-Only Systems (IOS)
- Vehicle-Only Systems (VOS)
- Vehicle-to-Vehicle Systems (V2V)
- Vehicle-to-Infrastructure/Infrastructure-to-Vehicle Systems (V2I/I2V)

Infrastructure-Only-Systems (IOS)

Once two traffic streams intersect at the same level and there is a risk of collision. The simplest approach to avoiding collisions and keeping the traffic flowing are rules such as right-of-way. Stop signs prevent vehicles which must give way from crossing the road in a thoughtless way. Roundabouts reduce the number of conflicting streams. Entering the roundabout, the driver only faces vehicles approaching at slow speed from the left. No conflicts with other vehicles are possible while leaving the roundabout, but maybe with crossing vulnerable road users. If the traffic demand reaches the limits of the capacity of the roundabout, which can be in the case of a maximum of 1000 passenger cars an hour for a one lane roundabout [SCHNABEL ET AL., 1997], traffic needs to be controlled by traffic lights. As the traffic lights are mostly installed to increase the traffic flow at intersections, the positive effect on the traffic safety at intersections is important, too. But there are also obvious approaches to reduce accidents at intersection as GERSTENBERGER [2015] reports. He describes that the starting point for a safe crossing of a junction is the early recognition of the intersection. The course of the road and the presence and visibility of advance direction sign and guide marker are useful for recognizing the loom of an intersection. For the construction of new intersections emphasis should be put on the avoidance for obstructing the drivers' view and distraction of the drivers' attention by billboards.

In addition to these typical approaches to ensure safe traffic flow at intersections, additional measures have been investigated, ranging from static or dynamic driver information at the roadside up to systems including infrastructure-based sensors. Already in 1995 YOSHIKAWA [US Patent No: 5,448,219, 1995] filed a patent application for a system preventing vehicles from colliding with each other as they cross intersections. The idea is to detected approaching vehicles on the main road using a sensor mounted at the roadside. Either a flashing “STOP” in the stop sign or a small bar mounted in the road with cyclically flashing lamps alerts the driver on the minor road if it is dangerous to cross.

YAN ET AL. [2005] describe a simple method for informing drivers whether they are still able to cross safely or not. A road marking is placed at the approach of intersections saying, “Signal Ahead”. If the driver starts to brake at the sign in the moment the light switches to amber, he is able to stop safely before the stop line. To determine the distance of the sign the usual speed at the approach needs to be estimated. A driver simulator test study showed that 74.3% of the red-light violations could be avoided by this road marking. WANG ET AL. [2012] propose an infrastructure-only system to reduce the impact of red light crossing. Three loop detectors in the vicinity of intersections identify red light violations. For a design speed of about 70 km/h, the first loop is about 100 m; the second about 60 m and the third loop detects the presence of the vehicle right in front of the stop line at a distance of 18 m. Once a red-light violation hazard is detected and likely to occur with a high probability, the system dynamically initiates an all-red interval within a few seconds. Instead of inductive loop detectors CHAN ET AL. [2004] propose the use of radar sensors. He observed vehicles approaching traffic lights using two radar sensors and demonstrated the benefit of continuous knowledge about the time-to-intersection and distance-to-intersection in generating proper warnings for vehicles at risk of violating red lights.

To prevent left-turn crashes with opposite-direction traffic WHITE ET AL. [2002] suggest an inexpensive, infrastructure-based, intersection collision-avoidance system. Radar, ultrasound, laser scanners, or inductive loops are suitable to detect the presence of vehicles turning left. For the opposite traffic, similar technology can be used to detect the speed of vehicles. If the situation is critical for a left-turning motorist, an infrastructure-based sign indicates an approaching vehicle so he/she can rethink his/her decision.

Vehicle-Only Systems (VOS)

To be independent from roadside-based alerts or any other entity, the automotive industry addresses collision avoidance systems in a way that makes vehicles self-supporting. The vehicle scans its surrounding and identifies critical situations to warn the driver or even intervene directly. As a prerequisite, the vehicle needs to be equipped with the appropriate sensing technology.

In the German INVENT project (2001-2005), onboard cameras in combination with appropriate image processing software are used to identify red traffic lights and stop signs [INVENT-BÜRO, 2005]. According to MEITINGER [2008] the stop sign assistant uses speed, acceleration, position of the gas pedal, brake pressure and steering wheel angle to estimate the drivers’ behavior and to determine whether they are about to stop or not. An acoustic and visual warning message is displayed to drivers if they are at risk of violating a red light or a stop sign.

For test purposes, an automatic safety brake action has been included, too. An onboard long-range radar system reaching up to 200 m is used to detect the oncoming traffic for a left turn assistant. Further information such as the steering wheel angle, the change of the steering wheel angle and position of the gas pedal is needed as additional input to assist the driver during a left turn maneuver. If a collision is imminent, the system warns the driver through a prototype human machine interface (HMI). In case the driver stops during the turn and turning is not safe, the system disallows to start again, which the test drivers liked most [BRANZ ET AL., 2005].

The effort on autonomous intersection collision warning systems that was started during the INVENT project, is being continued in the German *AKTIV* project (2008-2010) [AKTIV, 2011]. Stereo vision cameras [FRANKE ET AL., 2007] are used to detect crossing vehicles, cyclists or pedestrians with the right-of-way, enabling the onboard system of the vehicle to warn the driver in case of potential collision. Using further onboard sensors (radar, lidar und monocular cameras) collision avoidance, especially for protecting vulnerable road users, is being investigated and tested. WENDER ET AL. [2005] describe the use of high level maps for the classification of objects using an onboard laser scanner system for detecting the situation at intersections as an input for a collision avoidance system. However, the sensing capability of onboard advices is limited, as MEITINGER [2008] reports, especially at left turning maneuvers, when the turning vehicle needs to cross more than one lane and the line of sight of the sensors is obstructed by other vehicles. The use of wireless communication can fill this gap.

Vehicle-to-Vehicle Systems (V2V)

To fill the above-mentioned gap, two kinds of systems have been investigated: one relating only on the exchange of data between vehicles through wireless communication, the other combines data provided by onboard sensors and through communication between vehicles.

MILLER ET AL. [2002] address the hidden vehicle problem, which is troubling the Vehicle-only Systems, with a low-cost peer-to-peer beacon-based collision warning system. MILLER'S pure V2V-system includes information on the driving dynamics of the vehicle taken from the CAN-Bus, positioning data from GPS and information from other vehicles transmitted by Short Range Communication (DSRC), as well as by WLAN 802.11a,b and Bluetooth 802.15b. Based on this information, he predicts the vehicle's trajectories in a linear way and computes the intersection of the two lines. If the time to reach the intersection is identical for both vehicles, then they will collide and a warning will be issued. MILLER identifies the wireless communication range, the network latency, the vehicle speed, the tire-road friction coefficient, the driver response time and the accuracy of location and speed estimation as critical factors for collision avoidances systems. To enhance the information base, he recommends the integration of data provided by infrastructure-based entities.

SENGUPTA ET AL. [2007] propose another pure V2V-system assisting the driver especially in crossing uncontrolled intersections. The input data for this cooperative collision warning system is the position and information on driving dynamics of the vehicles hosting the system and of the other vehicles at the intersection. As the information is exchanged by wireless communication, each vehicle needs to be equipped with a transmitter. This onboard vehicle equipment is rather inexpensive compared to ranging sensors that could provide 360-degree coverage as the communication does. In contrast to MILLER, SENGUPTA improves the quality of the positioning data by fusing GPS data and data on driving dynamics of the vehicle with a Kalman filter. Furthermore, he uses a bicycle model based on an extended Kalman filter [REZAEI ET AL., 2007] to predict not only straight movements of the vehicle by considering additional data on the angle of steering wheel, the yaw rate and the wheel speed.

KLANNER [2008] follows a similar approach as SENGUPTA. In addition, KLANNER enables his system to compensate for varying inaccuracy of the positioning and includes the driver behavior while approaching the intersection. The data transmission ideally takes place directly between the vehicles. If direct communication is not possible because of larger buildings or any other object obstructing the view, KLANNER proposes that the vehicles themselves or a communication unit mounted at the infrastructure take the role of a repeater. The best position of an infrastructure-based repeater would be directly in the middle of the intersection, in which case the information could be transmitted perfectly into the different approaches of the intersection.

The partners of the *AKTIV* project [AKTIV, 2011] did research on combining onboard sensor information with information taken from the V2V-communication. This kind of system is sometimes also referred to as cooperative sensor fusing system. A left turn collision avoidance system has been implemented by the integration of a radar sensor, which provides also data on hidden objects, and data transmitted by the V2V-communication. An onboard camera to improve the localization of the vehicle, DGPS and data provided by the V2V communication in combination with a high level digital map is used to build a warning system especially for crossing motorbikes.

In the European project CyberCars2: Close Communications for Cooperation between CyberCars, a vehicle control system for safe intersections is being developed [ALONSO ET AL., 2011]. The project partners conduct tests with three vehicles meeting at the same time at an uncontrolled intersection. The vehicles are equipped with sensors, actuators and a V2V-communiction unit, and they can be driven either manually or autonomously. The aim is to test two different decision algorithms for priority conflict resolution at the intersection. The first method, the priority charts, is based on a relational database containing the graph representation of an intersection. A vehicle approaching an intersection will ask the database to obtain the paths leading into the intersection, and then will only consider the vehicles moving along these paths. By considering the positions, speeds, and next turn intentions of the other vehicles on the paths, the vehicle is able to determine whether it can continue or should wait and give way to others. The second method is based on priority levels. The vehicles determine whether they have the right of way by comparing their priorities using the next turn intention (which is sent within the communications package), the position, and the speed of the other vehicles.

Another approach dealing with traffic safety at intersections is presented by WATSON ET AL. [2013]. He generates a cooperative group of cognitive vehicles at a certain distance to each other. A cognitive vehicle in his understanding is equipped with different sensor technologies, has a human machine interface, actuators for automatic intervention or fully autonomous operation and a wireless communication device. Each cooperative group includes one vehicle being the group coordinator gathering and interpreting the information from the other group members and exchanging data with the group coordinators of neighboring groups. Based on this information, the proposed system executes a short-term prediction and identifies dangerous situations. Once a dangerous situation is detected, the system can either issue a warning to the driver or it can intervene autonomously by executing a cooperative maneuver. WATSON describes the action for a certain time interval of a vehicle through its acceleration and its steering angle. Before the next action is selected, a tree structure of decisions results when an action is applied for a certain interval of time. Each action leads to a new motion state of the vehicle. Certain losses can be assigned to each vehicle state, such as a loss for departing of the road and colliding with a vehicle or obstacle. The optimal tree of actions is computed by minimizing the minimum accumulated loss. To solve this optimization problem, WATSON uses mixed-integer linear programming. The system has been only tested in labor experiments and simulations so far.

Vehicle-to-Infrastructure Systems (V2I)

The last category of CAS is combining infrastructure components with the vehicle based systems to gain more data and widen the field of detection. The functionality of an ITS roadside station (IRS) starts as being just a communication hub and ends with an intelligent data fusion engine. In most of the systems the communication is bi-directional. That means that the term V2I automatically includes both communication directions.

In Japan, SUGIMOTO ET AL. [2000] presented a Driving Safety Support System (DSSS), which is a collision avoidance system based on infrared beacons. The infrared communication makes use of near-infrared rays as a communication tool to establish a two-way communication with the passing vehicles. The proposed system avoids accidents caused by vehicles making a right turn and vehicles approaching from ahead from the opposite lane (left-hand traffic) or caused by turning vehicles which fail to notice pedestrians or bicycles crossing a crosswalk. The vehicles are detected by cameras and the gathered information is processed by a decision-making unit on the roadside. If a dangerous situation is recognized, the driver can either be warned through an information panel at the approach of the intersection or via information transmitted directly onto the dashboard of the car by an infrared-beacon.

KOJIMA ET AL. [2005] perform driving simulator experiments and display camera pictures of the surrounding environment directly in the vehicles. The images of the camera are presented on virtual mirrors and the so called “NaviView” System assists drivers in recognizing objects in dead zones. The system has been tested successfully in a virtual environment. However, the authors do not provide a statement on how the images will be brought to the vehicle in a real-life system.

In the US, the Cooperative Intersection Collision Avoidance Systems (CICAS) Program has developed intersection safety counter measures within the Vehicle Infrastructure Integration (VII) environment [McHale, 2008]. The CICAS-Program comprises of three projects; the CICAS-Violation (V) prevents the driver from violating traffic signals or stop signs. The two projects CICAS-Stop Sign Assist (SSA) and CICAS-Signalized Left Turn Assist (SLTA) address safety problems due to the driver’s poor judgment of gaps in traffic. CICAS-SSA is dealing with lateral gaps in traffic and CICAS-SLTA with oncoming gaps in traffic.

According to Maile et al. [2011], the intersection portion of the system consists of a signal controller capable of exporting Signal Phase and Timing (SPaT) information, a local Global Positioning System (GPS), a geometric intersection description (GID) with in the RSE and 5.9 GHz DSRC radio. The vehicle part of the system includes a connection with the CAN-bus of the vehicle, GPS, a human machine interface and a 5.9 GHz DSRC radio, too. The equipped intersection broadcasts the SPaT message, positioning corrections and a small part of the geometric representation of the intersection to approaching vehicles. The vehicles receiving this information predict whether the driver will violate traffic signals or not. In case the driver is at risk of violating the signal, he is warned via a combination of visual/auditory/haptic brake pulse HMI. Nekoui et al. [2009] report another option. When the equipped vehicle approaches the intersection near the end of a green interval, the vehicle will receive a message from the intersection communication unit asking for its speed and position. The vehicle will send back the requested speed and position data. The RSE computes whether a moving vehicle is likely to run a red light. If this is the case, the vehicles on the conflicting approach will be warned of the potential danger. Maile and Nekoui further conclude that the test showed that CICAS-V is ready for a large scaled FOT. Maile et al. [2008a] provide detailed information on the concept, Maile et al. [2008b] report on test results and Kiger et al. [2008] present the preparation for the FOT.

The CICAS-Stop Sign Assist is comparable to the Japanese activities, but is mainly designed for rural intersections on US highways as Gorjestani et al. [2010] state. An infrastructure-based unit gathers data provided by detectors and receives data transmitted by the approaching vehicles. Based on that information, the presence of vehicles and the gap on the main road are identified. If it is not safe to cross, an infrastructure-based sign (Figure 2.4 and Figure 2.5) alerts the driver who must give the right of way. But there is also the possibility to warn drivers via their car's on-board HMI. The HMI will provide information indicating an unsafe condition to drivers on the minor road. According to reports on CICAS-SSA [Minnesota DoT, 2012], there are two possible future implementations of the system; in one scenario, information sent from the vehicle to the RSE would be used to adapt the warning timing, and the RSE would then broadcast the appropriate warning message to the vehicle. In the second scenario, the RSE would continuously broadcast dynamic intersection state data, and the OBU would use this dynamic state information to execute its threat assessment algorithm and alert the driver accordingly. Also, the concept of CICAS-SSA has been proven successful and the system is ready for Field Operational Test (FOT).

Figure 2.4 Red background, white letters indicating 5 seconds to the vehicle on the left [Gorjestani et al., 2010]

Figure 2.5 Vehicle approaching from the right too close [Gorjestani et al., 2010]

The CICIAS-SLTA basic research was finalized successfully and forms the basis for the design of a Field Operational Test (FOT) [Misener, 2010]. Based on the idea of similar equipment in every vehicle and all intersections as used in CICAS-V, the gaps of the oncoming vehicles are estimated and a warning is displayed to the driver in case of unsafe left turning. The information is either displayed in a driver-vehicle interface (DVI) or driver-infrastructure interface (DII). Figure 2.6 illustrates the two ways of interfacing the driver. One of the major findings of the test was the fact that, when the driver decided to stop, the presence or absence of a warning did not seem to influence the driver's rating on whether there had been enough time to turn or not.

Figure 2.6 CICAS-SLTA driver interfaces Misener [2010]

But not only in the U.S. or in Japan collision avoidance is being investigated. In Europe, as also briefly noted on page 68, the INTERSAFE 1 project uses the communication between vehicles and traffic light controllers along with onboard sensors (laser, camera) and a detailed map of the intersection to improve traffic safety [FÜRSTENBERG ET AL., 2006]. As a first step, an electronic map needs to be generated. Onboard sensors detect the objects and recognize the road markings to gather the necessary information to build the map. Secondly, the position of the vehicle itself and the positions of all other objects are detected and assigned to the map. Thirdly, the objects are tracked and classified and the data is combined with the information about the status of the traffic lights. As a fourth step, the potential conflicts of the ego vehicle are computed using the digital map and location of other road users. Finally, a fuzzy rule-base is built to reproduce the “human thinking” for the risk assessment and the driver is warned accordingly. In the INTERSAFE 1 project the scenarios crossing, turning and red-light running have been investigated successfully. Effectively only the red light assistance was established by using V2I-communication. The other scenarios were handled as vehicle only systems.

In the INTERSAFE 2 project, which is the successor of INTERSAFE 1, infrastructure sensors were included in the concept, as ROESSLER ET AL. [2010] report. The covered scenarios are similar to those of INTERSAFE 1. But the major innovation is the use of laser scanners installed at the top of the poles of traffic lights or street lamps. These scanners are able to survey nearly the whole intersection without being in danger of an obstructed view by stopped vehicles or pedestrians standing right in front of the scanner. This has been a problem in the case of laser scanners in the SAFESPOT project; the scanners were mounted at the bottom of the street (the next paragraph describes this approach in more detail). The other advantage of the infrastructure-based scanners is that they can detect vehicles which are not equipped with V2V-communication and can detect vehicles which the on-board sensors of a host vehicle cannot see due to a limited field of view. Furthermore, cameras enrich the spectrum of the infrastructure sensors. These cameras detect pedestrians and survey the road surface conditions. The collected information about the position of objects and road surface conditions, as well as the information about the traffic lights is transmitted to the vehicles at the intersection [PYYKONEN ET AL., 2010]. Based on this information the vehicles decide whether it is safe to cross or turn. Besides the denser equipment of the intersection with infrastructure-based sensors, the fact that the assessment of the situation takes place on-board of the vehicles is a major difference between INTERSAFE and SAFESPOT. In the SAFESPOT project the situation is assessed at the intelligence located at the intersection device.

Research on intersection safety continued in the German project Ko-FAS (cooperative driver assistance systems), as WEIDL ET AL. [2012] report. The project uses the SPaT (Signal Phase and Timing) message and the MAP message broadcasted by the IRS (ITS roadside station). SPaT includes information on the current and next traffic light status and the MAP message contains data on the topographical description of the intersection such as location of the stop line. Combined with positioning methods such as GPS, tightly coupled GNSS/INS and cooperative GNSS the assessment of the situation is conducted by object-oriented Bayesian networks. Based on the probabilities and the time to collision (TTC) values, the on-board system assists the driver in a warning strategy comprising three levels: Firstly, information that the TTC is larger than 3 s, secondly, that the TTC is smaller than 3 s and larger than 1 s and finally, that there is autonomous action of the vehicle.

As this short review shows, a lot of effort has been put into the development of systems trying to make intersections safer. The variety of the system comprises of systems using infrastructure-based technologies, vehicle-based sensor technologies or both. The database is enlarged by systems dealing with V2V- and V2I-communication and fusion information gathered by on-board vehicles sensors and infrastructures sensors. Approaches developed and tested in the INTERSAFE projects 1 and 2, in the SAFEEPOT project – the IRIS-System – or the CICAS initiative of the U.S. DoT family showed great success.

Nevertheless, it turned out that applications dealing with the improvement of traffic safety in urban areas are much more demanding in terms of data accuracy, latency times and reliability of the drawn decisions by the application. Therefore, cooperative intersection safety systems for avoiding collisions at intersections are not yet at the stage in development where they can be tested in a large scale FOT.

3 The Intelligent Cooperative Intersection Safety System

This section introduces the basic concept of the Intelligent Cooperative Intersection Safety System (IRIS) and presents the intersection scenarios covered by the IRIS-System. As data handling is important for cooperative applications, this section furthermore introduces data fusion concepts and herewith to the logical approach of the IRIS-System.

3.1 Basic Concept of IRIS

The aim of the European research project SAFESPOT was to develop and test new procedures and technologies for merging and interpreting data from intelligent vehicles and roadside sensors [SAFESPOT, 2010]. These technologies make it possible to extend the road user's awareness of the surrounding environment in space and time. The **I**ntelligent Coope**r**ative **I**ntersection **S**afety System (IRIS) is the answer to the first hypothesis *"It is possible to design a system, which is able to monitor and asses the driving maneuvers at an urban intersection"* proposed in the introduction of the thesis at page 2. The IRIS-System observes the urban intersection from a "bird's eye view" and identifies potential conflicts at urban intersections by computing the road users' trajectories and assessing the evolving situation. Warning messages are generated by an intelligent unit located at the infrastructure and transmitted by means of wireless communication to the engaged vehicle [SCHENDZIELORZ ET AL., 2008, SCHENDZIELORZ ET AL., 2013b].

The passing vehicles automatically transmit data such as their position and speed to the infrastructure via a vehicular ad-hoc network (VANET), which is a wireless computer network established between the communication entities of the vehicles and the infrastructure as soon as they are within the range of transmission. At the side of the road, the vehicle data is combined with information available at the infrastructure side, such as the control state of the traffic lights, data captured by road side detectors and static information about the geometry of the intersection. This set of data is forwarded to the data refinement and assessment components, which constitute the core of the IRIS-System. These components predict the trajectories of the vehicles, assess the evolving situation and trigger, if necessary, the message generator. The generated message is transmitted to the vehicle by means of VANET. After the message has been validated on board of the vehicle, it can be displayed to the driver on the in-vehicle human machine interface. Figure 3.1 depicts the described process chain.

Computing road user movement, information concerning position, speed and acceleration are required as a minimum. Data from laser scanners installed at the road side and data transmitted by the vehicles themselves are available for the IRIS-System. The cooperative vehicles transmit time-stamped information including their current position, speed and heading. In addition to this basic set, the acceleration, the status of exterior lights, such as the use of a turn signal, and the type of the vehicle (e.g. passenger car or emergency vehicle) is sent, too.

Besides the information about the road user, additional information concerning the current and future state of the traffic light is considered for the interpretation of the current and evolving situation. The task of the Data Receiver as part of the ITS roadside station (IRS) is to handle input from all these different data sources. The Data Receiver can be regarded as a common data gateway for external components or subsystems. For that purpose, it comprises various data interfaces for the different data sources. Furthermore, it carries out elementary plausibility checks on incoming data, such as range checks.

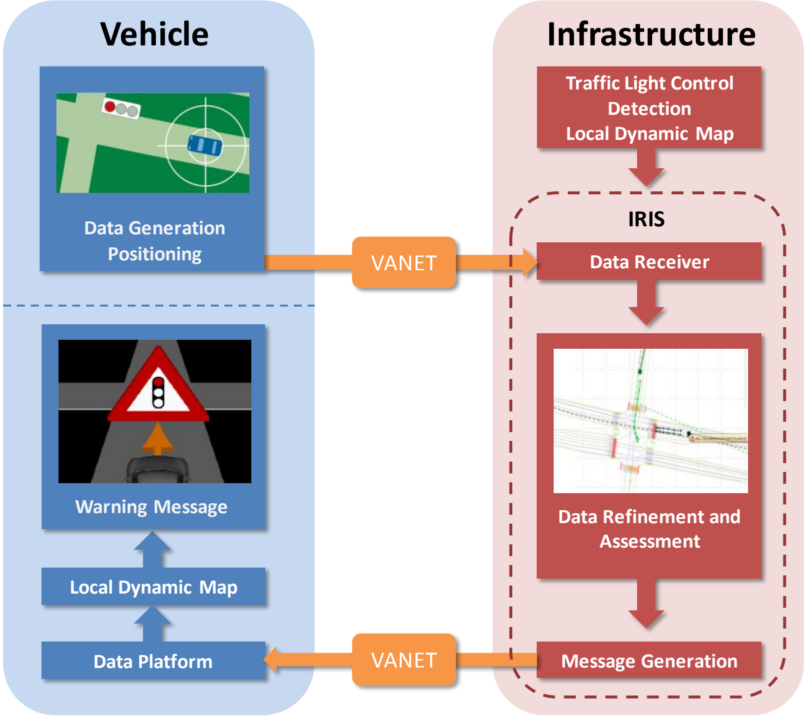


Figure 3.1 General process chain of the intelligent cooperative intersection safety system

The Data Receiver forwards the data to the *Data Refinement* and *Threat Assessment* unit through an internal interface. This unit is responsible for assigning available data sources pertaining to one certain object, such as vehicles. This way moving objects are map matched in the surrounding of the intersection to finally identify critical situations. As a first step, the data fusion process tracks moving objects, such as cars, and computes the reference of each single object on the static map. This map is available in the Local Dynamic Map (LDM) [PAPP ET AL., 2008]. The LDM offers a detailed description of the geometry of the intersection including lanes and stop lines. Subsequently, the possible maneuvers of the vehicle are estimated and its trajectories considering its relationship to the traffic light control status, to neighboring vehicles and other road users are predicted. The final *Threat Assessment* step analyzes the situation to identify critical situations. Once a safety critical situation is identified, the *Threat Assessment* decides on the appropriate action to avoid or mitigate the evolving situation. The result of the *Threat Assessment* - the warning message - is sent to the vehicles.

Covered Scenarios

Considering the accident analysis as reported in paragraph 2.3 and the technical possibilities, the concept of IRIS is designed to deal with the following:

- *Red Light Violation*: The aim is to detect imminent red-light violation as early as possible to warn all the road-users concerned. This intervention is divided into two stages. The first stage is to warn violating drivers in order to avoid the red-light violation. The second stage is to warn other affected road users in case a driver does not stop in time.
- *Right Turning*: While turning right, drivers must pay attention to cyclists and pedestrians moving parallel on the road. The aim is to warn drivers against a possible collision with a vulnerable road user.
- *Unprotected Left Turning*: During a left turn, the driver needs to pay attention to oncoming vehicles. IRIS assists drivers especially in the case of other vehicles blocking their view.

3.2 Concept of Data Refinement

Within the IRS, which is hosting the IRIS-System, many different types of data and information need to be collected from different sensing and detection technologies to run the system. This includes dynamic data received through data exchange between vehicles and the infrastructure, as well as static and dynamic data originating from various sources such as the Local Dynamic Map or traffic light controllers. These data need to be brought together to enable IRIS to reproduce the road users' movements at an intersection to a certain extend and to infer the criticality of a situation. Therefore, a concept for fusing data is needed.

WHITE [1991] defines data fusion as “a process dealing with the association, correlation, and combination of data and information from single and multiple sources to achieve refined position and identity estimates, and complete and timely assessments of situations and threats as well as their significance.” According to the German Road and Transportation Research Association [FGSV, 2003] “data fusion is a process which automatically detects, associates, combines and estimates signals and data sourcing for different kind of sensors. The aim is to identify the real world with a higher accuracy and reliability as it would be possible by just using one single data source or sensor.” What both views have in common is the combination of data from different sources to gain a better representation of reality. However, the definition of WHITE also includes the assessment of the situation itself.

Appling data fusion to transportation, the FGSV subdivides the data fusion process into four levels. Level 1 is dealing with the pre-processing of the raw data originating from sensors, such as bias corrects or map matching. The focus is on a single measuring point along a time line. This can be GPS positions of a probe vehicle, too. The result is adjusted data. The second level further processes these data to reconstruct traffic on a stretch of road. The result is further enriched with additional information gained from the transportation network. The output of this third level is information, which is further processed in the fourth level dealing with intermodal aspects of the traffic.

For traffic modeling and generation of traffic information, the view of the FGSV appears suitable. Nevertheless, nowadays the scope of applications reflects a broader variety than before the rapid development in computations and communications. To improve traffic safety at urban intersections by using the technology cooperative systems provide, it is necessary to draw conclusions on a rather circumscribed area in time and space. According to Hall et al. [1997], the understanding of data fusion in the subject of multi-sensor fusion for military proposes covers a hierarchical transformation between the observed parameters that are provided by multiple sources, and a decision regarding the characteristics of the observed entity and the interpretation of those in the context of the surrounding environment and relationships to other entities. Figure 3.2 depicts the level of inference described above from low to high.

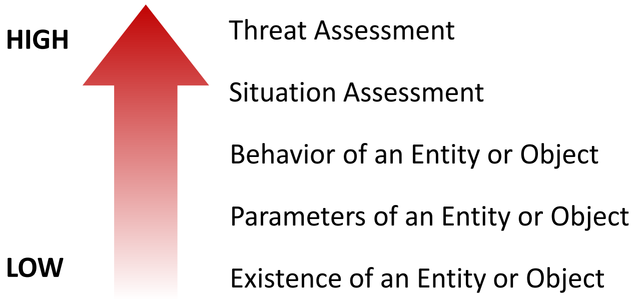


Figure 3.2 Inference hierarchy referring to Hall et al. [1997]

This basic concept leads to the model for multi-sensor data fusion developed by the U.S. Joint Directors of Laboratories (JDL) Data Fusion Group [Hall et al., 1997]. The fusion process begins by interfacing the sources of information that represent the input to the process. The gathered input data is passed through the “backbone” of the fusion model to ultimately produce the result that needs to be made available through a suitable interface. It should be pointed out, that it is not considered essential for each data input to pass through all function levels. The required process steps depend on the type and level of the data item and on the desired outcome. By setting out the basic elements of the data fusion process and by clearly defining the different steps involved, the model offers a valuable basis and an underlying structure.

Data originating from different sources and providing similar or additional information on an object or situation needs different concepts of fusing and integrating the information. According to Ruser et al. [2007], there are no limitations on what type of information can be fused and in which way it is fused, in general. He distinguishes three basic types of data fusion to generate a common understanding and to describe the challenges a big variety of data sources brings along. Figure 3.3 depicts these types: the competitive, the complementary and the cooperative fusion.

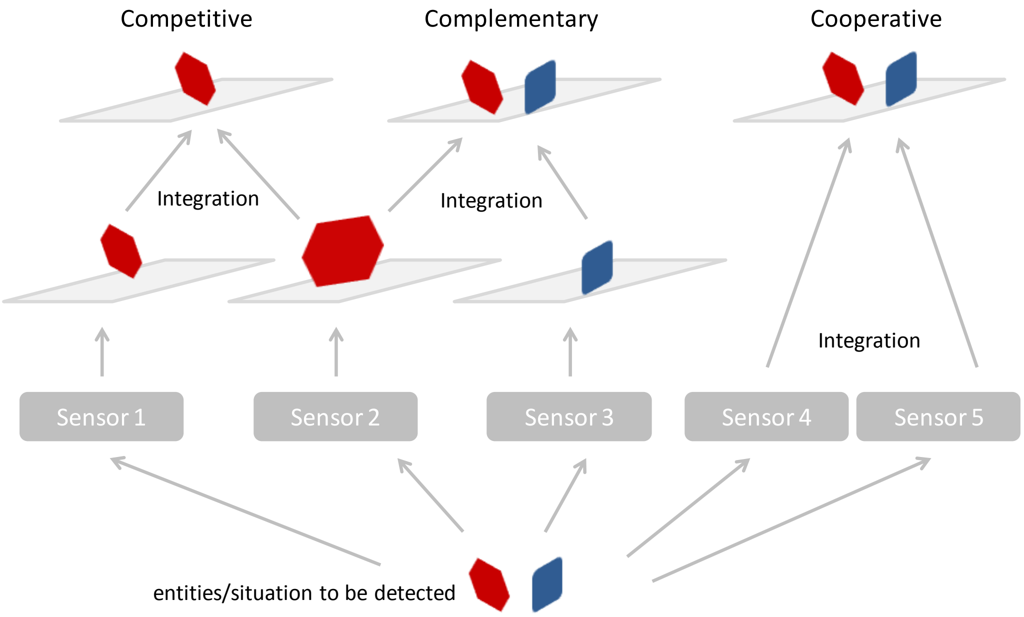


Figure 3.3 Classification of data fusion types referring to RUSER ET AL. [2007]

Competitive fusion: This type covers the fusion of redundant sensors (two or more sensors of the same type providing the same information about an entity) to increase the reliability in case of sensor defects. An example is the inductive loop detector and the radar sensor covering the same part of the road. Both provide information on the presence of vehicles passing by, so these pieces of information compete.

Complementary fusion: This is the fusion of two or more sensors of the same type covering not overlapping or partly overlapping surveillance areas to achieve measurements about objects which a single sensor cannot provide. As an example, the induction loop detector and the radar sensor are cover different parts of the road from one another.

Cooperative fusion: This type of fusion merges data and information of different sources to achieve information that a single sensor is not able to detect. The integration of information happens at sensor level. The loop detector and the radar sensor, for instance, cover the same area. The presence of a vehicle is integrated with the information on the speed of that vehicle, which is detected by the radar sensor. Another example is the spacing of two vehicles, which could be estimated using the position of those two vehicles. Another task of cooperative fusion is also to increase the quality of the output data of a single sensor. Cooperative fusion does not mean the integration of data provided by vehicles and infrastructure in terms of a cooperative system.

3.3 Logical Architecture and Functions of IRIS-System

The JDL-Model forms the underlying idea of the IRIS processes running at the infrastructure side. The JDL-Model was successfully used in the PReVENT project ProFusion dealing with the data fusion on board of a vehicle [PARK, 2005]. Figure 3.4 presents the logical architecture of IRIS, the input data sources and the actuation. The data refinement processes are in line with the JDL Data Fusion Model.

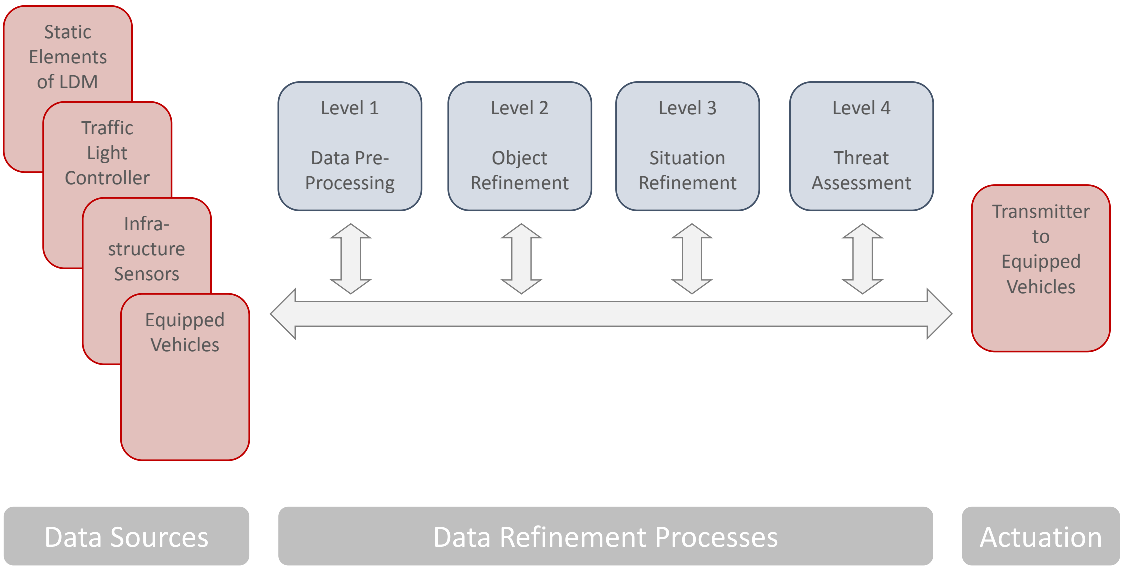


Figure 3.4 Logical architecture of IRIS-System referring to STEINBERG ET AL. [2001]

Pre-Processing is located at Level 1. This step involves the pre-processing of the input data and has the aim of correcting bias, standardizing inputs and extracting key information before fusion with other data. The amount of pre-processing required is therefore dependent on the characteristics of the sensors involved. Transferred to the Intelligent Cooperative Intersection Safety System, the Data Receiver represents the front-end of the processing and data fusion in the IRS. It is responsible for receiving data from the different sensors, from external centers and from the VANET. The following two refinement processes at Levels 2 and 3 have the purpose of reconstructing the traffic scenario as precisely as possible or necessary to provide the basis for identification and assessment of a safety-critical situation.

Object Refinement

The purpose of the *Object Refinement* at Level 2 is to combine sensor data and to obtain a reliable and accurate estimate of a specific object. The *Object Refinement* combines several items of data to increase the accuracy, consistency or reliability of the information describing an object (e.g. vehicle, obstacle, traffic event). The fusion process may be competitive or complementary. Complementary fusion implies that the aim is to create a composite picture from data originating from different objects, physical areas or attributes. Considering the competitive fusion, the data refers to the same object but is derived from different types of sensors (or even different measurements from the same type of sensor or information source). Competitive fusion combines the information concerning one single road user at the intersection.

Therefore, the *Object Refinement* is not a trivial task and gets more important in C-ITS as more data sources are available. Imagine a hypothetical scenario with an intersection equipped with more than one infrastructure side sensors, e.g. laser scanners and cameras observing the situation, as well as with equipped vehicles transmitting data. The objective is to clarify whether the sensors detected the same object. And if the object, e.g. a vehicle, provides data itself, it needs to be figured out whether this data refers to an object the sensors are aware of. The *Object Refinement* clarifies that there is an object of interest and then consolidates the attributes of that object, such as position, speed or acceleration. These attributes may be different despite referring to the same object, because they are sensed or transmitted in different points in time and by different types of sensing systems. In the case the *Object Refinement* is not considered and dealt with properly there might by more than one computed picture of the objects in the observed area. In reality this consolation is not very likely due to the high investment needed for equipping an intersection with that amount of sensing technology. However, it is conceivable that a vehicle is transmitting its data or data about other objects and the area is covered by an infrastructure side sensor as well.

The Object Refinement located at the infrastructure-side can take place at a sensor level and at a central level right in the IRS. In the SAFESPOT project *Object Refinement* at the sensor level combines data of the laser scanners and data received from the vehicles [Kutila et al., 2007a]. This assures refinement of the sensed objects by the laser scanner and provides more accurate and reliable data on the objects. Furthermore, time alignment is done in order to assure that the components of the object refinement at a central level receive the data in predefined time steps. If the data is not refined at the sensor level or if another data source or type of sensor needs to be considered, *Object Refinement* at central level is necessary. For implementing the IRIS-System at real intersections the Object Refinement was located at sensor level being all laser scanners. No additional sensors such as cameras were used for detecting objects. So, the competitive fusion concept was not developed further since for testing the IRIS-System at the real intersection only one laser scanner was used for detecting vulnerable road users, but not the vehicles. Data about vehicles are transmitted to the IRIS-System by the vehicles themselves. Therefore, it was not necessary to elaborate the *Object Refinement* at central level. The link to the traffic light controller and the static part of the LDM complete the set of input data, as Figure 3.4 presents. However, the *Object Refinement* at central level comprising the competitive fusion needs to be investigated in more detail in future so that the IRIS-System is able to deal with different kind of sensors input data on the certain objects.

Situation Refinement and Threat Assessment

The *Situation Refinement* executed at Level 3 results in a composite description or estimation of an evolving situation. This is based on an assessment of the relationships between a set of objects and possibly also their relationships with the surrounding environment to achieve a result sensors are not able to measures directly. The *Situation Refinement* does cooperative data fusion. In the case of the IRIS, the *Situation Refinement* is responsible for map matching objects to the Local Dynamic Map to estimate possible maneuvers of the vehicles and to predict their trajectories into the future. The objective of the *Threat Assessment* at level 4 is to assess the potential impact or threats associated with alternative hypotheses or forecasts based on the outcome of the *Situation Refinement* process. It determines the criticality of the evolving situation and decides whether a warning needs to be issued or not. At the end of the fusion process chain, the message generator sends the appropriated message to the road user. The whole variety of data, including sensor data, support data and knowledge bases, as well as interim processing results, needs to be handled and “steered” through the process systematically. The *Situation Refinement* and the *Threat Assessment* are the core elements of the IRIS-System. The *Situation Refinement* of IRIS consists of two components, the Intersection Maneuvers Estimation (IME) and the Intersection Movement Approximation (IMA). These components and the *Threat Assessment* of IRIS are described in detail in the following sections.

Short Recapitulation

The JDL Model provides a structured approach for the data processing with in the IRIS-System. The data sent to the Data Receiver, is forwarded to the data refinement processes. According to the JDL Model these are the *Object Refinement, Situation Refinement* and *Threat Assessment*. For the IRIS-System the *Situation Refinement* and *Threat Assessment* are the most important building blocks providing the functionality for estimating the vehicles maneuvers, for predicting the vehicles’ paths and for analyzing the situation whether a road user is in danger or not. These two building blocks are described in detail in the following sections.

Concerning the *Object Refinement,* it is either already done directly at the sensor level or at the center level. Because of the conditions at the test bed, only one laser scanner was installed, no *Object Refinement* at a center level was necessary. Therefore, no further effort was put in development of the *Object Refinement*. Nevertheless, it is a very important task one should have in mind in the case it is planned to integrate more data originating from different sensors.

4 Estimation of the Maneuver

The prediction of evolving situations at intersections and therefore the prediction of trajectories of vehicles approaching intersections starts with the Intersection Maneuvers Estimation (IME). The aim of the IME is to predict the maneuver which a driver is going to execute at an intersection. For each vehicle, the system is aware of, the IME therefore computes the probability for executing a certain maneuver. The driver's possible micro route decisions are straight, left or right. U-turns are not considered by the algorithm. Notably, the IME does not calculate the future trajectory of a vehicle. This computation is conducted in a separate process step. Hence, the outcome of the IME is not the position where the vehicle might be at a certain time in the future, but the possibility for a certain maneuver.

The IME considers probe vehicle data such as position, speed and turn signal activation. Furthermore, the procedure makes use of the current and predicted traffic light status and the typical speed at the approach of intersections, as well as the position of stop lines. The result of the procedure is a collection of assignments of vehicles' positions to geometric representations of its maneuver possibilities. For that task, the positions of the vehicles play an important role. Therefore, the beginning of this section reviews the positioning of moving objects divided into onboard positioning systems and roadside tracking systems.

4.1 Positioning and Tracking of Moving Objects

Knowledge of the current situation and its prediction into the near future is essential for the detection of critical situations at the intersection. Therefore, it is significant for the IRIS-System to have proper knowledge of the position of vehicles, cyclists and pedestrians at intersections. In general, one can distinguish two ways of retrieving the position: either the position of the moving object is detected directly by a special sensing system such as a camera or a laser scanner installed at the roadside or the moving object actively transmits its position. In the latter case, the moving object determines its position by an onboard positioning system and transmits the position to the roadside equipment. For the IRIS-System, the positions of vehicles are transmitted via an onboard positioning system, whereas the positions of cyclists and pedestrians are determined by an infrastructure based laser scanner system.

4.1.1 Onboard Positioning System

The system generally used to retrieve the absolute position of a vehicle is data from Global Navigation Satellite Systems (GNSS), such as the U.S. Global Positioning System (GPS), the Russian GLONASS (globalnaja nawigazionnaja sputnikowaja sistema) or - in the near future - also the European Galileo System. All these GNSS follow the same working principle, with GPS being the one available on a nearly global scale at any time. Therefore, this working principle is explained in the following section.

General Working Principle of GNSS Using the Example of GPS

The Global Positioning System (GPS) currently works with a minimum of 24 satellites, which circle around the earth on different orbits at an altitude of more than 20,000 km. Each of these satellites is equipped with a precise atomic timing device and transmits its own position (x_i, y_i, z_i) with a time stamp t_i regularly on a high frequency of about 50 times a second. A GPS receiver on Earth receives these signals. Knowing the exact time t at the receiver, it is possible to compute the signal transit time $(t_i - t)$ and the distance to the satellite d_i by multiplying the transit time by the speed of light c; then the GPS receiver knows that it is on a sphere around the satellite's position with radius d_i. Figure 4.1 depicts the approach showing two dimensions.

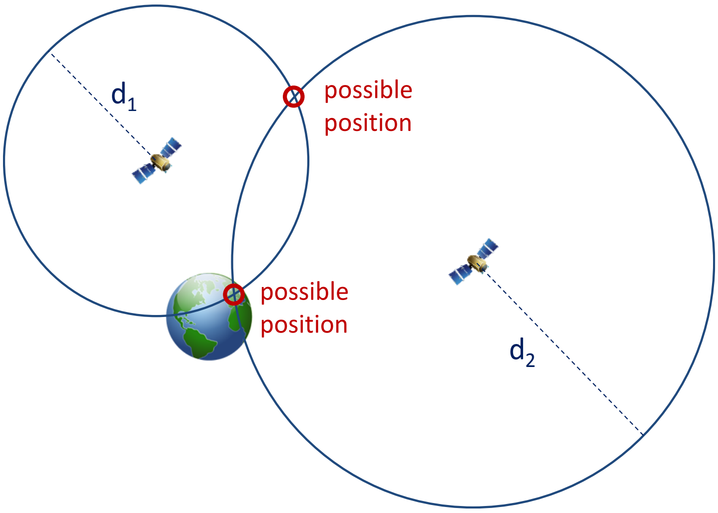


Figure 4.1 Principle of GNSS positioning for two dimensions

Having determined the spheres around three satellites, the receiver estimates its position (x, y, z), which is the intersection of the three spheres. A fourth sphere allows for estimating even the time t, by solving the simplified equation (5.1) for the four satellites. For more details see [Seeber, 2003].

$$d_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} = c \cdot (t_i - t) \qquad i = 1, 2, 3, 4 \tag{4.1}$$

In the context of estimating the position of a GPS receiver it is important to mention the term "accuracy". According to Quddus [2006], accuracy is defined as *“the nearness of a measurement to the standard or true value”* and should not be confused with the term precision. Precision, as he continues, *“is the degree to which several measurements from the same medium agree with each other”*. As Dodel et al. [2010] state, the accuracy of the estimated position is higher, the more orthogonally the spheres around the satellites intersect each other. This implies that accuracy is proportional to the volume of a reversed pyramid the four satellites generate with the GPS receiver at the peak. The smaller the volume of that pyramid, the lower the accuracy. Independent from the number of satellites visible, the volume of the pyramid would be nearly equal to zero if all satellites in view were in one line. Besides the satellites constellation and clock errors, SEEBER mentions further factors influencing accuracy. He separates them into signal processing errors, such as multipath effects and influences of the ionosphere and troposphere the signal must pass through, as well as into receiver dependent errors, such as noise in the observation of the signal or hardware delays. In urban areas, besides the obstruction of view of the satellites through buildings, the multipath effect plays a major role as a source of error. Buildings and trees reflect the signals transmitted by satellites. Consequently, the GPS receiver does not only receive direct signals but also the reflected signals, which take longer to reach the receiver. The different signal transit times for the same piece of information then leads to vagueness.

Because of these error sources, the achievable accuracy of latest GPS positioning devices under optimal conditions is between 3 m and 20 m, as [REIT, 2010] and [KLEINE-BESTEN ET AL., 2012] stated. Galileo even asserted to reach about 4 m accuracy [SCHUBERT, SCHLINGELHOF ET AL., 2007]. For some services, this is sufficient in the subject of ITS and DAS, but for other services it is not enough, as Table 4.1 reports.

Application or Service	**Accuracy longitudinal (m)**	**Accuracy lateral (m)**	**Availability (%)**
Vehicle theft protection	100 - 250	5	99.7
Transit vehicle control	30 - 50	5	99.7
Logistic and fleet management	5 - 30	5	99.7
Navigation and route guidance	5 - 20	5	99.7
Emergency location	5 - 10	5	99.7
Collision avoidance	1	1	99.7

Table 4.1 Requirements for the positioning of a selection of ITS and DAS services referring to QUDDUS [2006] and DODEL ET AL. [2010]

For a service such as vehicle theft protection the requirement in the accuracy of positioning is rather low as it is sufficient to locate the stolen vehicle in specific area. For transit vehicle control, fleet management or route guidance the requirements are much higher compared to the vehicle theft protection application. For those the accuracy of the position in longitudinal direction, i.e. in driving direction, can vary from 5 m to 50 m as the vehicle needs to be located accurately on the transit or road network for computing the current traffic situation for example. In lateral direction, i.e. perpendicular to the driving direction, the requirements with 5 m are higher than in longitudinal direction to distinguish, among others, parallel roads on which the vehicle is driving based on the position of the car. Collision avoidance systems have the strongest requirements on the determination of the position. In lateral and in longitudinal direction the accuracy should not be less than 1 m in order to run the system. Therefore, the accuracy of standard GPS devices needs to be improved to run collision avoidance systems properly.

To reduce the sources of error, the receiver hardware and software is constantly being improved. Besides that, additional information is considered to improve the accuracy of the positing devices. Common representatives of these methods are Differential Global Positioning System (DGPS), Inertial Navigation Systems (INS), and Matching Systems (MS).

Differential Global Positioning System

The method of Differential Global Positioning System (DGPS) reduces the errors in position by using correction values. DGPS needs the exact position of a point on Earth on which a GPS antenna is mounted; this position serves as the DGPS reference station. As soon as the exact position of this reference station and the position of the satellite is known, the precise distance to the satellite can be determined. The comparison of measured and computed distances provides correction values. These values are valid in a range of about 200 km around the reference station. The correction values are transmitted to the mobile GPS receiver via mobile communication, for instance. The GPS receiver uses the correction values to improve the distance measured to the satellites and therefore the positioning accuracy. The position accuracy can be up to 1 dm. In Germany, the Satellite Positioning Service (SAPOS) provides GPS correction values for the whole country. Besides the terrestrial reference stations, there are also reference satellites in the orbit. The Satellite Based Augmentation System (SBAS), such as the US Wide Area Augmentation System (WAAS) or the European Geostationary Navigation Overlay Service (EGNOS) provided correction values determined by geostationary satellites. The position accuracy is about 1 m to 3 m. For more details, see [DODEL ET AL., 2010].

Inertial Navigation Systems

Inertial Navigation Systems (INS) have been widely established for improving the positioning accuracy in vehicles, so that navigation systems could be independent of any additionally incurred service and communication costs, as is the case with DGPS. The basic idea of INS is the Deduced Reckoning Method (DRM). The DRM uses speed, heading and time elapsed since the last determination of the position. Based on a known earlier position and direction, the positional changes are anticipated by adding traveled distance and changed headings; the movement profile of the vehicle is deduced. The INS generate the information necessary to run the Deduced Reckoning from acceleration rate and yaw rate. Gyroscopes and acceleration sensors capture this data as a part either of the GPS receiver or of the vehicle itself. An odometer can be used to measure the rotation of the wheel and count the number of wheel revolutions. These revolutions are then transformed into traveled distance. All these sensors provide the measured data with a certain bias, which needs to be taken into account deducing the movement profile. WENDEL [2011] provides more information on INS.

Matching Systems

Matching Systems are the reaming systems, which are important to mention, for improving the position accuracy. These onboard systems provide a reference to the position of the vehicle by matching pre-stored information about the road network (map matching), the terrain (terrain contour matching) or prominent objects such as building (image matching) while driving [DODEL ET AL., 2010].

Map matching systems compare the absolute position provided by the GPS receiver with the digital map of the road network and correct the position by including additional information such as speed or direction. The position of the vehicle is “clipped” onto a certain street. Therefore, the gained maximum accuracy is about the width of the road the vehicle is driving on, which is higher than normal GPS accuracy. The improvement of absolute position and proper operation of land navigation systems is strongly related to the accuracy and uncertainty of digital maps. Usually, digital maps represent the road network based on single links, normally the centerline of a road and nodes, describing the intersections. Additional information, such as number of lanes, lane width or turning restrictions are normally assigned as attributes to the links and nodes, but do not exist as graphical displayable items. QUDDUS [2006] therefore distinguishes two main errors:

- A topological error describes omitted or simplified features of the real world, such as curves, lane markings, and roundabouts in the digital map
- A geometric error describes the displacement of the map features in the digital map compared to the real location.

As collision avoidance systems have strong requirements for the position accuracy. In most cases commonly available digital maps need to be enriched with additional features to compensate for topological errors and to run the system properly. Additional data capturing of geometric information reduces the geometric error, too. The better the positioning system of the map data-capturing unit gets, the smaller the resulting geometric error will be.

As map matching systems gain advantages in areas where digital street networks are available, the terrain counter matching system are used in rural areas and off roads. Here the matching process also takes the altitude of the terrain and rivers or rail tracks into account. Both systems only operate with internal sensors and pre-stored information. According to DODEL ET AL. [2010], image matching or landmark-based positioning systems use a-priori information, too. These are mostly prominent objects such as buildings, but can also be rivers or woodlands. Onboard sensors such as cameras or laser scanners monitor the surrounding of the vehicle and the system compares the scanned objects with the stored objects to update the position of the vehicle relative to the matched images.

Landmark-based Vehicle Positing Systems

Also in the SAFESPOT project, accurate positioning techniques play a major role, not only for the IRIS-System. Based on communication networks such as ultra-wideband or wireless local area network, as well as based on the detection of landmarks, the accuracy of the positioning was improved, as SCHUBERT, SCHLINGELHOF ET AL. [2007] report. As MATTERN ET AL. [2008] states, differential GPS receiver and INS can achieve very good results already, but these are often quite expensive. For example, the Leica 1200 DGPS with real time kinematic provides accuracy up to 2 cm, but at more than 1,000 Euro is rather expensive. Landmark-based positioning seems to be a promising and reasonable alternative for solving the problem of accurate positioning, as nowadays premium vehicles are already often equipped with laser scanners or cameras. However, to run a landmark-based positioning system, the position of the landmarks must be available on the digital map. In a broader sense, the landmark-based positioning system can be understood as a kind of map matching system. However, further details than usual are need in a digital map as well as special sensors are required.

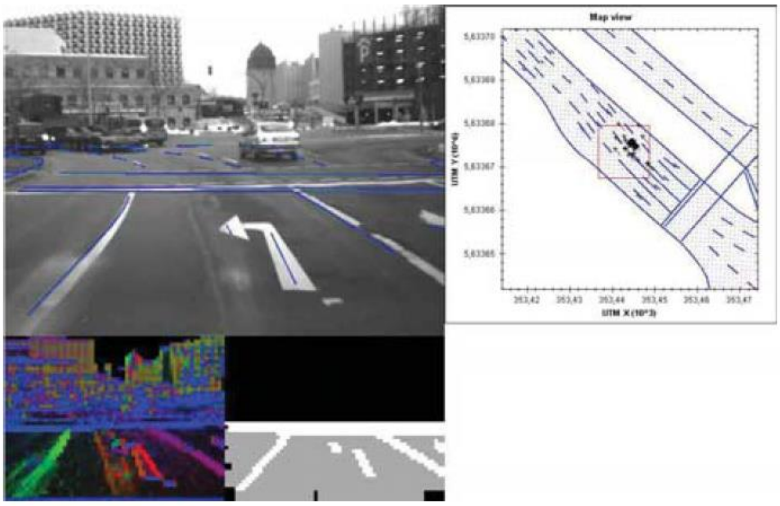


Figure 4.2 Landmark-based vehicle positioning system: grayscale image with the re-projection of the line landmarks based, the structure tensor image in pseudo colors, class image prediction, and a map view with the particles [MATTERN ET AL., 2010]

For detecting the landmarks, MATTERN uses a monocular camera with a resolution of 640 x 480 pixels and an update rate of 30 video frames per second. The so-called camera-based vehicle localization algorithm by MATTERN ET AL. [2010] utilize the images of the landmarks in combination with a low-cost GPS receiver, a digital map containing the landmarks, as well as vehicle odometry. The state of the vehicle is described through longitudinal x and lateral y position values, heading ϑ, velocity v, yaw rate ω and longitudinal acceleration a. The authors use polylines to model landmarks and curbs. In addition to the landmarks, information on the road surface, asphalt or concrete, is stored in the digital map. By sorting the surface information, also the residual amount of the overall world becomes known. The grey values of the camera image are transformed into a pixelated pseudo image. Once the type and location of the landmark have been stored in the digital map, the algorithm is able to predict a complete class image containing information on the road surface, land markings and areas beside the roads. This means that the algorithm generates a class image prediction of the map features, as the camera would see it (see Figure 4.2).

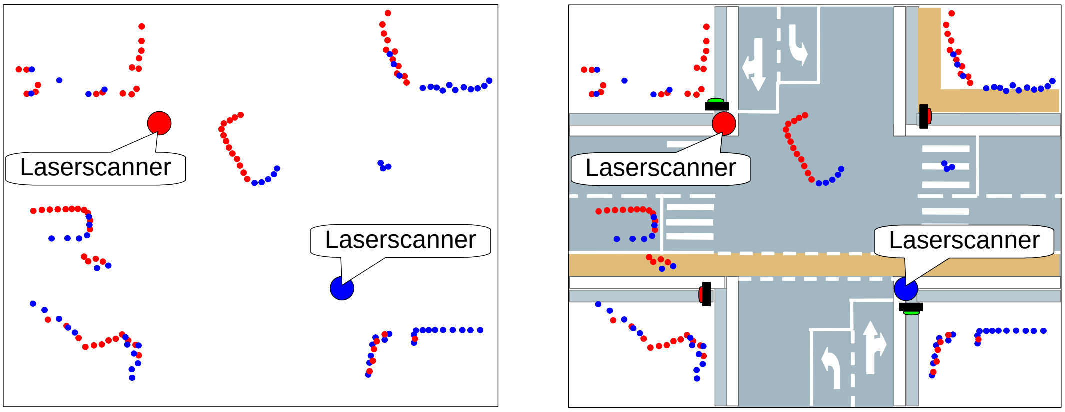
By combining the pseudo image and the predicted image, a probability for observing a certain feature can be estimated. By combining this probability value with the GPS position, an update of the vehicles state can be computed. The authors compared the landmark-based positioning system described above against the Leica 1200 DGSP with real time kinematics. The statistical evaluation of the positions errors shows that the mean of the directed position is 0.93 m with a standard deviation of 0.42 m. These results can be considered as lane-level accurate. For detailed information on the algorithm itself and the testing, see [MATTERN ET AL., 2010]. A similar approach is possible with laser scanner technology, too, as FÜRSTENBERG ET AL. [2006] report.

4.1.2 Roadside Tracking Systems

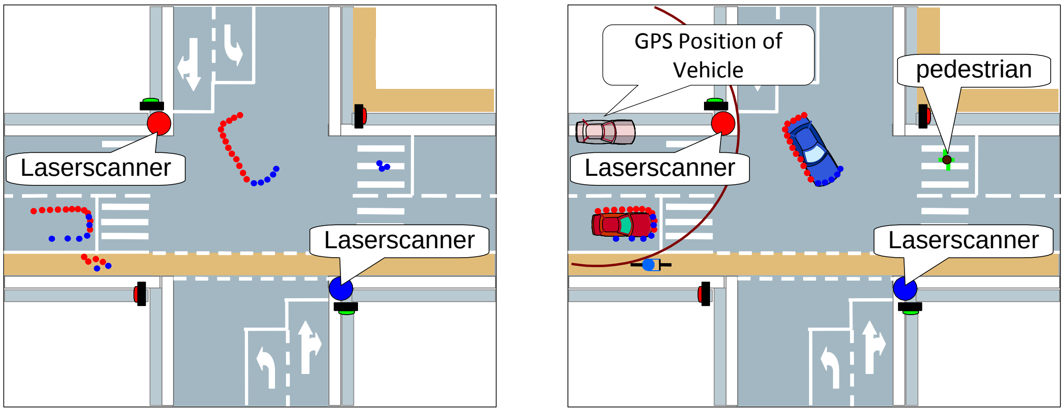
Besides the positioning systems on board of vehicles, sensors installed at the road side can also provide information on passing by vehicles. In general, the road side sensors are widely known to detect the presence of a vehicle or its speed at a certain specified small area of detection. Examples are inductive loops or radar detectors. The major difference is that the detection systems for an infrastructure-based collision warning system such as IRIS do not only have to detect the presence of objects. To a greater degree, it is also significant to track objects and provide positions, driving directions and speeds of vehicles. The advantage of these kinds of systems is that it is obvious where the sensor has been mounted. So, in general, these systems generate an estimation of the objects' position in relation to their own reference position. This paragraph presents two examples for tracking objects from the road side; one is based on laser scanners and the other based on cameras.

Infrastructure-based Sensor Raw Data Fusion

In the SAFESPOT project, laser scanners are mounted at the road side and the data of these scanners are fused at a sensor level with vehicle information transferred to the infrastructure and with static map information stored in the LDM for a more reliable and robust tracking and classification [KUTILA ET AL., 2007a]. The captured raw data of each laser scanner is merged into a single range profile (Figure 4.3a). Next, information on the surrounding static entities provided by the static map of the LDM is overlaid with the scan profile (Figure 4.3b). Based on this superposition, the system distinguishes between scan data, representing background objects and scan data at foreground objects, such as vehicles or pedestrians (Figure 4.3c). As the background information is not interesting, it is eliminated and only the scan data resulting from the road users is left. The following process step clusters the single scan points into groups, each representing one real object, and the established objects are tracked. The tracking compares the segment parameters of a scan with predicted parameters of known objects from the previous scans. Unrecognized segments are treated as new objects. Road users are classified by their typical outline using only the geometric data. Pedestrians are identified by the movement of their legs while walking.



a) Laser Scanner Raw Data b) Raw Data with Static Map Superposition



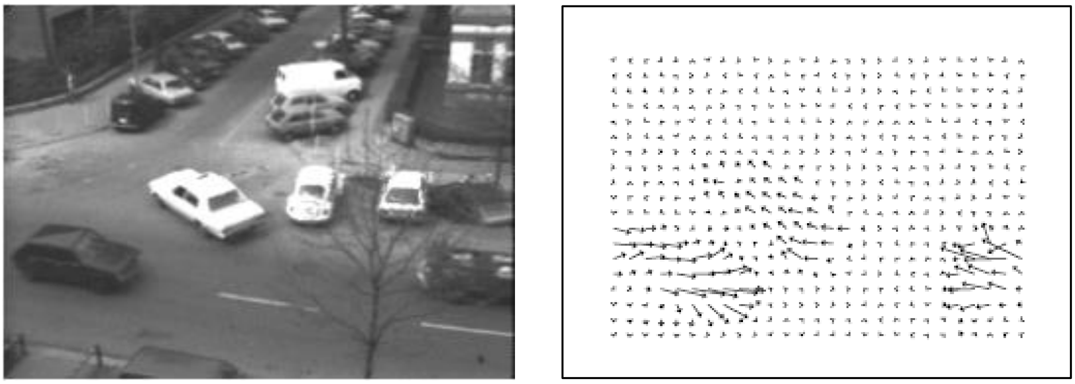
c) Background Elimination d) V2I Data Association

Figure 4.3 Roadside tracking of road users by a laser scanner system [Kutila et al., 2007a]

Further optimization is achieved by adapting the probability for an object class based on its position within the static map and static vehicle information provided via VANET. A major challenge for including the data sent by the vehicle is the association to the proper vehicle detected by the laser scanner. In the most challenging case, the received position of a vehicle is only based on normal GPS. This poor position accuracy causes a large search area for association processes. In Figure 4.3d the red vehicle sends its position and the red circle around the vehicle describes the corresponding inaccuracy of the position. The situation gets even more complex, the more vehicles there are at the intersection to be detected. In this case, additional information such as position, driving direction and speed needs to be considered for calculating association probability for each detected vehicle. A central unit collects the raw measurements of the single scanners and the additional information and compute the positions and speed of the scanned objects. The achieved accuracy is up to 0.5 m for the position and 0.8 m/s for the speed of the scanned objects at a detection range of about 200 m. Each object is assigned to certain class such as car, bike or pedestrian. A further enhancement would have been to assign to each object also its dimensions. But these was not foreseen in project. The raw measurements of the scanners were not provided to the IRIS-System as IRIS is designed to include information e.g. on position and speed of an object, but not raw data of sensors. This makes the IRIS-System independent from the type of sensors as long the requested data is provided in an understandable format. The data fusion of the laser scanner raw measurements was further developed and tested in the INTERSAFE 2 project [ROESSLER ET AL., 2010].

Vision-based Tracking System

Another tracking system also investigated in the SAFEPOT project is based on camera observations in combination with image processing techniques [KUTILA ET AL., 2007b]. Calculations based on Displacement Vector Field (DVF) provide an estimation of the movement direction of elements in the picture without any a priori knowledge of the shape of these elements (see Figure 4.4). The DVF is a matrix with vectors that represent the speed and direction of a pixel in a sequence of images, and allows the system to segment moving objects and separate them from their background.



a) Camera Image b) Displacement Vector Field

Figure 4.4 Example of the displacement vector field of a camera image [KUTILA ET AL., 2007b]

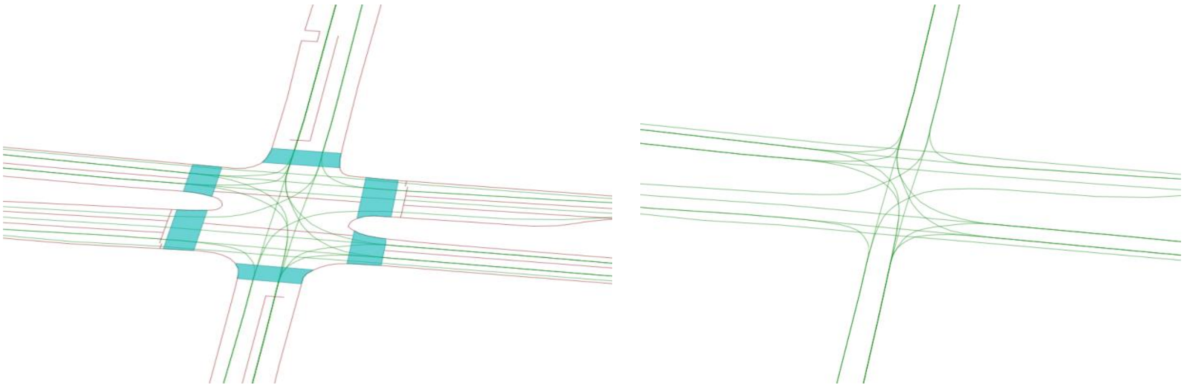
This allows an almost immediate estimation of the vehicles’ direction and speed. To achieve this, the image needs to be pre-processed first. This makes the images smoother and enhances the contrast of the edges, so noise is removed from the image. The DVF identifies separated moving zones of the image by its velocity, and validates those using characteristics such as the size of the patch, orientation or the lack of symmetry of a shape. Once a valid object has been detected, the global velocity and its direction must be calculated from all the values of the DVF. By installing the cameras at a high point, e.g. at a pole, the achieved position accuracy is up to 1.0 m and the detection range is about 100 m. This system was not installed at the test intersection of IRIS.

Used Positioning System for IRIS at the Intersection

For the IRIS-System the laser scanner is used to provide data on pedestrians and cyclists passing by. The data about the vehicles is taken from the periodic beacon signals the vehicles transmit. Each vehicle is equipped with an onboard positioning unit refining the raw sensor or DGPS data. Therefore, the vehicles provide high-quality positioning data in the range of about 0.5 m to 2 m and no filters such a Kalman Filter are required at the IRS. Having collected the data of the road users and the traffic control, the next step is estimating the maneuver of the detected vehicles.

4.2 Reference Tracks

Besides the vehicles' position the idea of *reference tracks* is mandatory [SCHENDZIELORZ ET AL., 2013b] for estimating the possible maneuvers and predicting the trajectories of vehicles at intersections in the IRIS-System. These reference tracks reflect the most likely path of vehicles and bicycles through the intersection as they perform a certain maneuver. Therefore, reference tracks are static representations of typical driving lines of vehicles or bicycles turning at an intersection or passing it.



a) Reference tracks, lane markings (red) and pedestrian crossing (turquoise boxes)

b) Only reference tracks

Figure 4.5 Representation of the reference tracks at an intersection

They are static polylines that are part of the Local Dynamic Map. Each reference track starts at a lane leading towards the intersection, matching the centerline of that lane, and ends at a lane exiting the intersection. This means that the reference tracks overlap at the incoming and exiting lanes. Furthermore, there might be more than one reference track representing the path for a left turn, for instance. The left-turning vehicles enter the intersection at the same lane but may have two lanes for leaving the intersection after turning. So, this phenomenon would be modeled using two different reference tracks. Figure 4.5 depicts the reference tracks as green lines.

It needs to be pointed out that the RTs used for the IRIS-System are an estimation of the most likely path. Many vehicles would describe a family of paths rather than one single line. While turning at an intersection the vehicles are able to take different paths for the same turn. ALHAJYASEEN ET AL. [2011] gathered video data on paths vehicle take during a left turn at six different Japanese intersections. The reference point for constructing the path for each vehicle is the center-front of the vehicle. According to his observations, intersection angle, corner radius and the number of exit lanes are the most significant factors that affect vehicle maneuvers. But also, the vehicle type and the existence of pedestrians and cyclists influence the path of a vehicle during turning.

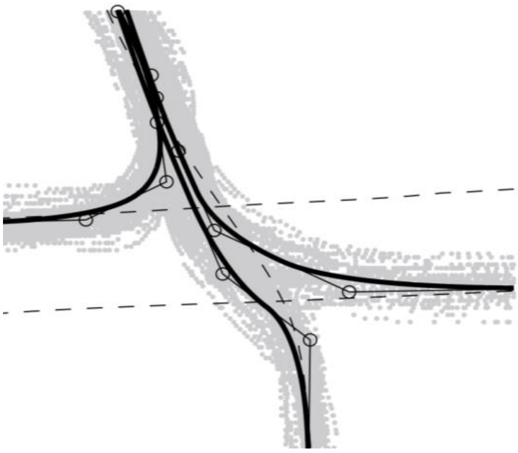


Figure 4.6 Paths of vehicles crossing and turning at an intersection including an average path (black) [EICHHORN ET AL., 2013]

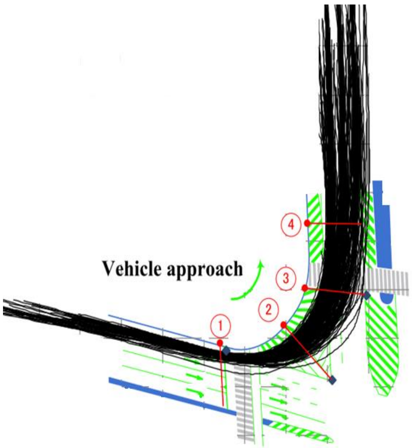


Figure 4.7 Paths of left-turn vehicles with two exit lanes at a Japanese intersection [ALHAJYASEEN ET AL., 2011]

Figure 4.6 represents the paths of vehicles crossing and turning at an intersection based on GPS-Signals. Figure 4.7 shows the family of paths at an intersection with two exit lanes at a Japanese intersection. Both figures illustrate the scattering of the paths of the vehicles. In the case of two or more lanes in one driving direction, specific reference tracks for each lane take into account this scattering between different lanes. However, the concept of the RTs fails to model the spread of the paths within a single lane. Based on his observations, ALHAJYASEEN developed a statistical model to reconstruct the most likely path as a function of intersection geometry, vehicle type and the existence of pedestrian and cyclist ways. EICHHORN ET AL. [2013] followed a similar approach to reconstruct the geometry of an intersection in his work. For the IRIS-System, such a large investigation with test drives was not possible. Therefore, the RTs are constructed manually considering the geometry of the intersection.

The manually constructed RTs are a weak point of the IRIS-System. Firstly, they shape of the RTs is a rough estimate. The shape is not considering the different paths of vehicle crossing and turning at the intersection. Secondly, the RTs need to be constructed for each intersection IRIS is installed by hand. An automatic self-learning process would be handsome, meaning that the tracks of the vehicle passing the intersection are analyzed for constructing the main path of the vehicles representing the RT for this certain maneuver. However, even having the most lily path for the RTs there is still a drawback remaining. The vehicle traded in IRIS will always be assigned to a RT as well the prediction of the movement will be done along the RT. Therefore, an error might be inherent in the prediction as some vehicles might not go along the RT in reality. Also, movements of the vehicles which are not in line with the traffic rules such as going along the bicycle path cannot be modelled. Nevertheless, for proving the concept of the IRIS-System the use of the RTs seemed to be promising as it is rather easy to implement and no huge data analyses beforehand was necessary.

While discussing turning vehicles at intersections, another important point to consider is the vehicle's dimension. Every vehicle describes a tractrix during the turn. This tractrix results from the fact that the tires which are not directly controlled by the steering wheel are pulled. These pulled tires describe a smaller radius than the front tires, if the front tires are the ones being controlled by the steering wheel (Figure 4.8). The longer the vehicle is, the larger the difference between the radius of rear and front tires will be and the larger the space required for the turn will be. This means that for a normal passenger car the difference is not that significant, but for a large truck it certainly is.

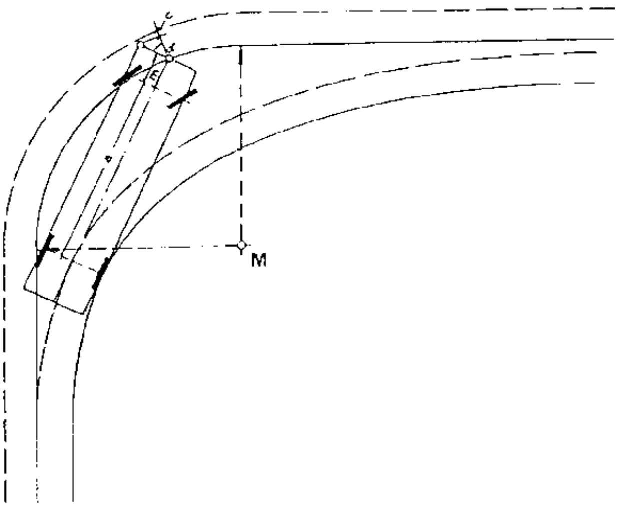


Figure 4.8 Idea of the tractrix for a vehicle turning right [BUSCH ET AL., 2013]

This aspect cannot be modelled with RTs and it not necessary for the IRIS-System, too. The task of IRIS is to avoid collisions with other road users and not to describe the space required while turning. We assume that the drivers are normally aware of the tractrix of their vehicle. So, the truck driver for example needs to reach out far more than the passenger car driver, which leads to a different track during the turn. It would be possible to construct different RTs for different vehicle types. But this was not done, as the focus was set to normal passenger cars at this stage of the investigation. The vehicles are modeled as single points reflecting the geometrical center of a standard vehicle. During the threat assessment, the vehicle dimensions are considered by shifting the point of interest from the geometrical center to the vehicle front by adding the half length of the vehicle. Therefore, the system does not only deal with collision areas but with collision points, too.

For predicting trajectories, it is not sufficient that the reference tracks reflect only the path of the vehicles. In addition, they offer the typical speed v_k^{typ} as a static attribute for each polyline segment of the RT, which can be derived from the current speed limit and the curvature of the road. The typical speed represents the speed a normal passenger car is going to drive at the intersection, assuming uncongested traffic conditions and no traffic control. As there was no possibility to gather data on the speed of turning vehicles, these values needed to be estimated. The speed values for clearing the intersection proposed by the German Road and Transportation Research Association in the Guidelines for Traffic Signals (RiLSA) [FGSV, 2010] formed the basis for that estimation. However, these speed values are rather low estimates because of the increase in traffic safety the planned control is able to provide. Therefore, the values for the typical speed values are slightly higher than the RiLSA-values, which is 7.5 m/s at narrow curves (radius<10 m) and 9 m/s at wide curves (radius>10 m).

4.3 Geometric Map Matching

The core of the *Intersection Maneuver Estimation* (IME) is the geometric map matching procedure for intersections presented in [SCHENDZIELORZ ET AL., 2013a]. Common map matching algorithms integrate positioning data from Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS), with digital spatial road network data. The general propose of these map matching algorithms is to determine the spatial reference of a vehicle location by identifying the corresponding digital road segment the vehicle is travelling on [QUDDUS ET AL., 2007]. Often a vehicle’s position is shifted onto the identified road element. This is especially the case in navigation systems. In the IRIS-System, the geometric map matching determines the respective road element and reference track, which are within a given distance of that position, for a given position of a vehicle, but does not shift the position. The geometric map matching takes into account the position of the vehicle, the moving direction vector (if available) and the normally distributed sigma value of the positioning uncertainty. The output contains several <road element, lane> pairs and reference tracks. All those matching items have probabilities that indicate the likelihood that the object is located in that position. Note that with respect to their probabilities, the <road element, lane> pairs and reference tracks must be considered independently.

The map matching process on lane level detail is not a trivial task, since the vehicle positions, which are determined based on in-vehicle GNSS, always include uncertainties that may be in the range of meters (especially in urban areas). To obtain better position values than those from common GPS devices, special positioning techniques were developed in the SAFESPOT project [SCHUBERT, SCHLINGELHOF ET AL., 2007]. Nevertheless, in order to establish a vehicle's position, probability distributions need to be considered and the vehicle should not be handled as sharp point. Considering this, two important consequences follow:

- The mapping of a position z_i of a vehicle i to a reference track k is a probability value p_{ik} with $0 \leq p_{ik} \leq 1$.
- A vehicle i can be mapped to several reference tracks $k_1, k_2, \dots k_M$ with different probabilities $p_{ik_1}, p_{ik_2}, \dots p_{ik_M}$ and $\sum_j^M p_{ik_j} = 1$.

Before computing the probability for the presence of a vehicle on a certain lane of a road element or reference track, some preparatory work must be completed. As the implemented system must be able to run in real time, the performance is an important attribute of collision avoidance systems. The task is to quickly identify the polyline segments that are within the error range of the vehicle's position. A complex intersection with a high number of reference tracks or road elements was mapped and each reference track is represented by a polyline. As a result, many items must be checked to determine whether the segment is within range or not. A special search concept accelerates this process. This concept superimposes a grid over a predefined area of interest. This area should be at least as large as the communication range. During the test at the real intersection more than 500 m on the main road could be reached. This leads to an area of interest which should be larger than 500 m.

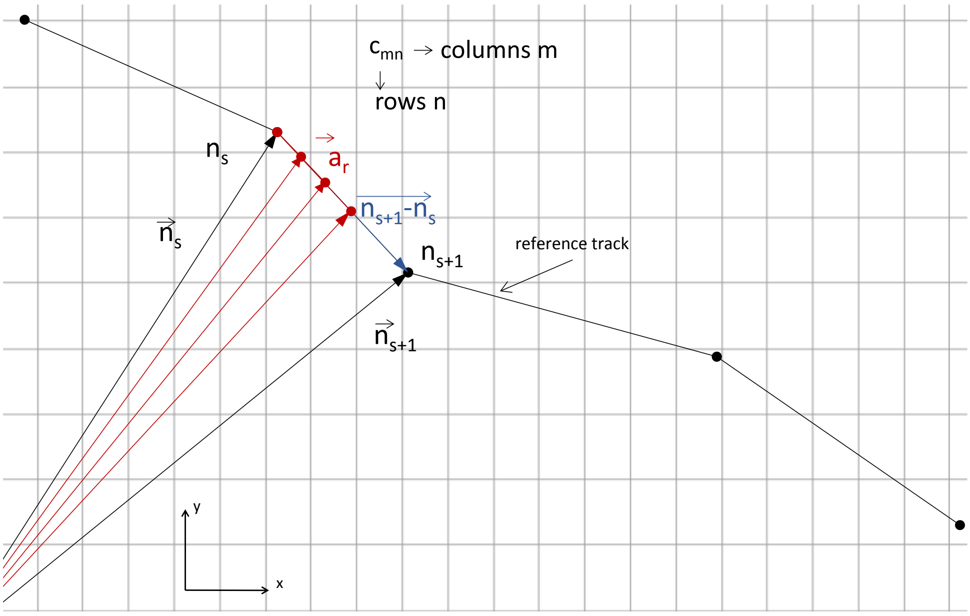


Figure 4.9 Aligning grid and reference track

The stretch of the grid in x and y-direction is defined by a bounding box which contains all nodes of the polylines in the area of interest. The square root of the total number of nodes N in the bounding box provides an estimation of the number of cells needed in each dimension of the grid to reduce the computational effort. The length or the height of one cell c_{mn} is the area of the grid divided by the number of rows or columns, respectively. For example, the area of interest at the real intersection was set to 830 m. The number of points was 181, which led to 13 rows and cells each. The size of one cell is therefore about 64 m in square. Once the grid is constructed, the cells are filled. For all reference tracks and for all polyline segments the RTs consist of, the number of cells covering a segment is computed.

In Figure 4.9 the depicted two consecutive nodes n_s and n_{s+1} are the starting and end point of one segment s of a RT and the vector $\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}$ represents this segment. The auxiliary vector $\overrightarrow{a_r}$ starts at the end point of vector $\overrightarrow{\mathrm{n}_{\mathrm{s}}}$ and paces out the vector $\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}$. The procedure (eq. 4.1), which is depicted in Figure 4.9 computes the vector $\overrightarrow{a_r}$ using an integer counter r and the minimum width of a cell w_c.

$$\overrightarrow{a_r} = \overrightarrow{n_s} + \left((\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}) \cdot \frac{r}{\mathrm{R}} \right) \quad \forall\, 0 < r \leq R, r \in \mathbb{Z}\,, \tag{4.1}$$

with $R = |\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}| / w_c$.

This procedure provides a new point on the segment. By taking the x-coordinate of that point, the distance to the lower x boundary of the grid can be computed. As the width of the cell is known, the spatial index of the column can be obtained by dividing the distance by the width. The spatial index of the row is computed analogously. Having computed the grid index, all lanes of a road element are assigned to the cell pairs of road element id and lane id. The grid concept is another representation of the coordinates of points in the area of an intersection using the grid index. This minimizes the search space for road elements and reference tracks in the area surrounding a vehicle. These preparations are performed only once in the initializing phase of the IRIS-System.

Now the *Intersection Maneuvers Estimation* processes the received positions of the vehicles. Once the beacon information of a vehicle is received, the IME will compute the grid coordinates for that position and the coordinates for the neighboring cell which is closest to that position. This enables the system to cover the road elements which are assigned to the adjacent cell if the vehicle's position z_i is close to the border of the cell. For each road element of the adjacent cells, the closest distance to the centerline of the road element is computed. The closest distance is the orthogonal projection of the vehicle's position onto the polyline segment. To decide whether a projection is possible and the vehicle is not positioned before or after the segments, three scalar products (sp) are computed:

- sp_1 is the inner product of $\overrightarrow{\mathrm{a}_1}$ and $\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}$
- sp_2 is the inner product of the zero vector and $\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}$, which means that the position z_i is exactly matching n_s. In this case, the scalar product equals zero.
- sp_3 is the inner product of the $\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}$ with itself, which means position z_i is exactly matching n_{s+1}. In this case the scalar product equals $|\overrightarrow{\mathrm{n}_{\mathrm{s}+1}} - \overrightarrow{\mathrm{n}_{\mathrm{s}}}|^2$ as $\cos\varphi_z = 1$ for $\varphi_z = 0^{\circ}$.

If $sp_2 \leq sp_1 \leq sp_3$ which is $0 \leq sp_1 \leq |\overrightarrow{n_{s+1}} - \overrightarrow{n_s}|^2$ the orthogonal distance to the polyline segment is computed by using equation (4.2) below:

$$d_{ik} = ((\overrightarrow{n_{s+1}} - \overrightarrow{n_s}) \cdot \lambda_{ik} + \overrightarrow{n_s}) - \overrightarrow{z_i} \qquad \forall\, i \in \mathcal{I}, k \in \mathcal{K} \tag{4.2}$$

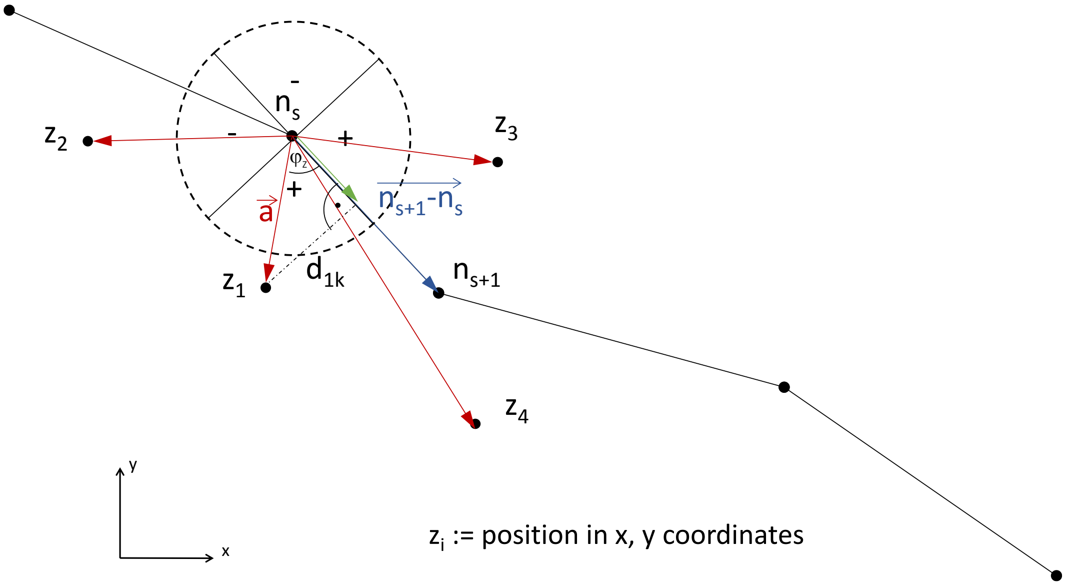


Figure 4.10 Determination of projection of vehicles' position z_1 to z_4

With the line indicator λ_{ik}, which is defined as the length of the orthogonal projection of z_i (green arrow in Figure 4.10) in proportion to the length of the segment itself multiplied with the cosine of φ_{z_i}:

$$\lambda_{ik} = \frac{\overrightarrow{z_i}-\overrightarrow{n_s}}{\overrightarrow{n_{s+1}}-\overrightarrow{n_s}} \cdot \cos\varphi_{z_i}, \tag{4.3}$$

with $|\overrightarrow{z_i} - \overrightarrow{n_s}| \cos\varphi_z$ being the orthogonal projection of position z_i onto the polyline segment. The value of λ indicates the position of a point to a segment of a poly line as the Table 4.2 shows:

Value of λ	**Position of point z in relation to the segment**
< 0	z before segment
= 0	first point of the segment and z match
> 0 and < 1	z in between the segment
= 1	last point of the segment and z match
> 1	z beyond the last point of the segment

Table 4.2 Interpretation of the line indicator

In addition to the orthogonal distance, the angle of the polyline segment with the speed vector $\overrightarrow{v_i}$ of the vehicle is computed. The next chapter describes the concept used to estimate the probability of the maneuvers at intersections based on these basic computations and additional input values.

4.4 Probability Refinement

For a procedure to refine the probability of executing a certain maneuver (left, straight, right) the following points must be into account [SCHENDZIELORZ ET AL., 2013a]:

- the position of the vehicle in relation to the polyline segment, which is the orthogonal distance $d_{ik}^{\perp}$,
- the speed vector in relation to the polyline segment, which is the angle ω_i,
- the standard deviation of the direction of the vehicle η_i,
- and the status of the turn signal of the vehicle b_i.

The result of this procedure is a collection of vehicle position assignments including probability values. The computed assignments to the road elements or reference tracks are approached independently, meaning that the sum of probabilities on reference tracks originating from one single approach to the intersection is equal to 1. The IME determines lane probability distributions from the information available and combines these distributions to create single mapping probabilities for the reference tracks.

To estimate the geometric probability p_{ik}^{geo} for the vehicle i on the reference track or lane of the road element k, we integrate the probability density function (pdf) over the lane width w. The Gauss error function (4.4) is used to compute the cumulative probability function (cpf). It is assumed, that the errors follow the law of large numbers and are therefore normally distributed. This assumption provides the basic for calculating the geometric probability. Equations (4.5) to (4.7) describe the steps of the calculation of p_{ik}^{geo}:

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-t^2} dt \tag{4.4}$$

$$F(x) = 0.5\left(1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right) \tag{4.5}$$

$$p_{ik}^{geo} = F(0.5w - d_{ik}) - F(-0.5w - d_{ik}) \tag{4.6}$$

$$p_{ik}^{geo} = 0.5\left(erf\left(\frac{-0.5w - d_{ik}}{(0.5w + \sigma_i)\sqrt{2}}\right) - erf\left(\frac{0.5w - d_{ik}}{(0.5w + \sigma_i)\sqrt{2}}\right)\right) \tag{4.7}$$

Where σ_i represents the standard deviation of the vehicle's position and d_{ik} is the orthogonal distance from the polyline segment of the reference track. The expectation is, that the position of the vehicle is exactly at the centerline of a lane, meaning exactly at a reference track $k;$ so $\mu = \overline{d_{ik}} = 0$. The geometric probability is the probability that a vehicle is driving on a certain lane. Therefore, the lane width w needs to be considered. It is set to 3.0 m in the urban environment as this is the width of a standard lane.

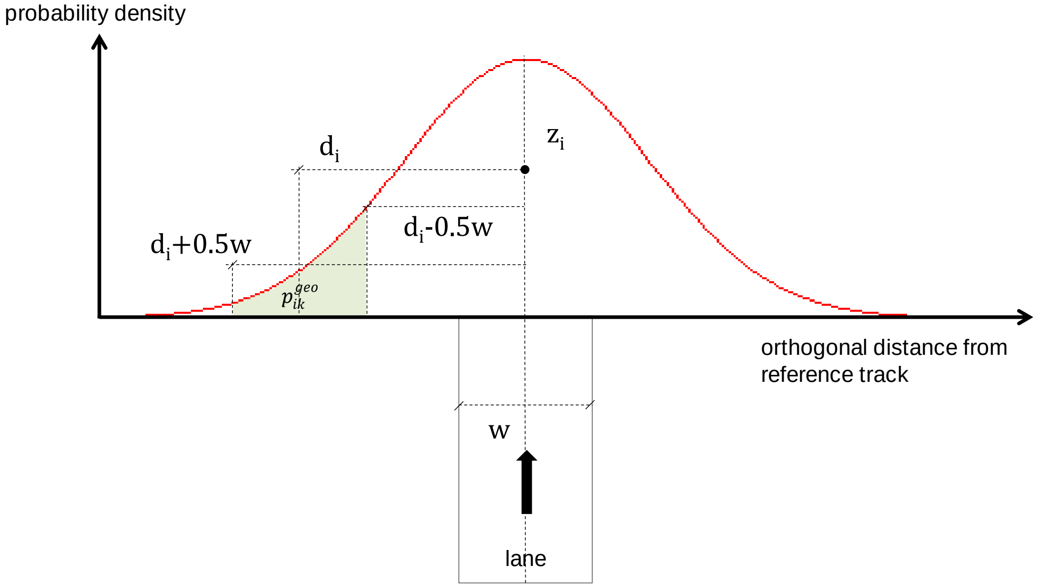


Figure 4.11 Illustration of the computation of the geometric probability

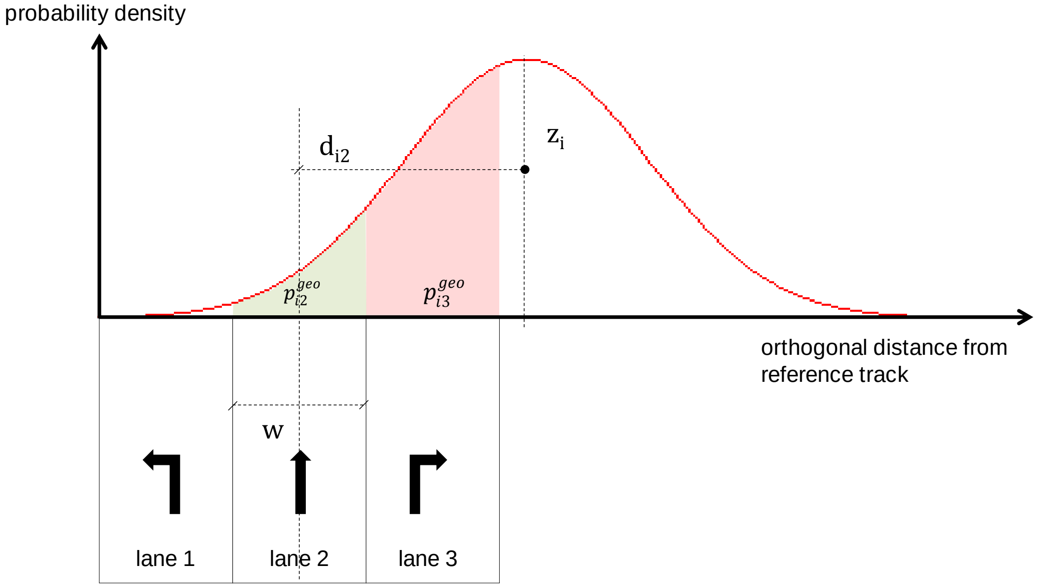


Figure 4.12 Illustration of geometric probability matched to lanes

Using equation (4.6) we compute the cpf assigned to the vehicle's position over a reference track k for each d_{ik}. By adding and subtracting the half lane width from the distance we get the limits of integration. Figure 4.11 and Figure 4.12 display this approach. In addition, the standard deviation is enlarged for the half lane width $0.5w + \sigma_i$. This flattens the pdf, the cdf starts earlier to increase its value but not that rapid as it is the case having a lower standard deviation. This approach considers that we do not need to be exactly at the centerline of a lane and lanes on the boundaries are assigned larger probability values.

To this point, the estimation of p_{ik}^{geo} does not consider any further information except d_{ik} and the standard deviation. Next the speed vector in relation to the polyline segment, which is the angle ω_i, is considered. Each deviation of the speed vector impairs the probability because the vehicle might be in another lane or change lanes. Therefore, the influence of ω_i is considered by adding the factor $e^{-\omega_i^2}$ (see Figure 4.13 for illustration). To include the inaccuracy of the vehicle's direction η_i the standard deviation of the vehicle's direction is considered by the factor $1/\eta_i^2$. That means that the larger the standard deviation of the vehicle's direction gets, the less the influence of ω_i is reduced as the reliability of the vehicle's direction decreases.

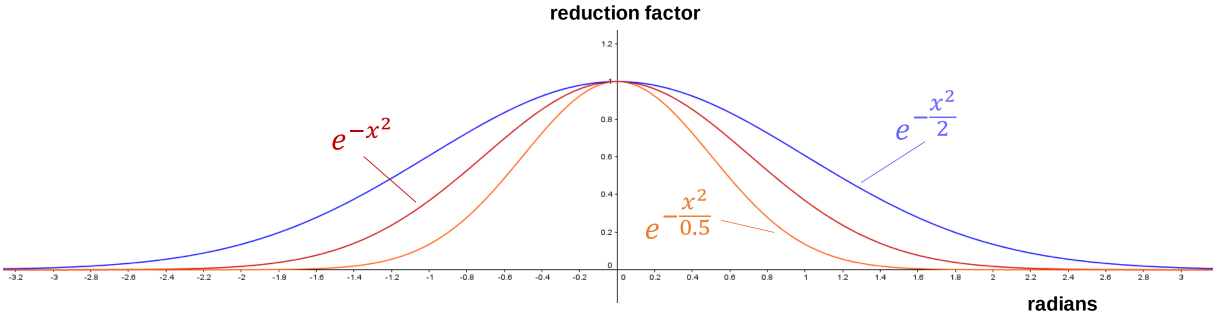


Figure 4.13 Reduction factor function example for the geometric probability because of speed vector

Finally, the status of the turn signal is included. Each status b_i has an influencing factor f_i^b. If no turn signal is used at all, the probability for the estimation that the vehicle is going straight is increased following relation (4.8). The remaining estimates are not influenced at all.

$$f_i^b(b_i \mathrel{\widehat{=}} off\,) = 2.0 \qquad \forall \text{ vehicles going straight} \tag{4.8}$$

$$f_i^b(b_i \mathrel{\widehat{=}} right) = 4.0 \qquad \forall \text{ vehicles turning right} \tag{4.9}$$

$$f_i^b(b_i \mathrel{\widehat{=}} left) = 4.0 \qquad \forall \text{ vehicles turning left} \tag{4.10}$$

In the case that a left or right turn signal is used, the estimates for the direction the turning signal is indicating the factor 4.0 is included in the estimation according to the relations (4.9) and (4.10). These factors are a rough estimation and have not yet been validated by an experiment. If a turn signal is used, we assume that it is very likely that the vehicle will turn. If a turn signal is not used, we must consider that a turn is still likely, therefore the value of the factor for $b_i \mathrel{\widehat{=}} off$ is reduced, but is not 0. In paragraph 7 there are experiments documented considering different factors for including the turn signal status in the algorithm.

The final probability for the vehicle's maneuver is computed by equation (4.11):

$$p_{ik} = p_{ik}^{geo} \cdot e^{-\frac{\omega_i^2}{\eta_i^2}} \cdot f_i^b \tag{4.11}$$

The last step is the normalization of the probabilities for the vehicle i on the reference track or lane of the road element k, as equation (4.12) shows:

$$p_{ik}^{norm} = \frac{p_{ik}}{\sum_k p_{ik}} \ \forall \ k \in h, h \in H \tag{4.12}$$

with $H = \{h \in H | h\ entry\ approach\ of intersection\}$

The result of the Intersection Maneuvers Estimation (IME) is a normalized probability p_{ik}^{norm} for each vehicle and each reference track in the range of the vehicle. As the RTs represent a certain driving maneuver at the intersection, the result of the IME can be interpreted as probabilities for certain maneuvers. The main input values are the position of the vehicle and the status of the turn signal. Furthermore, the speed vector and the standard deviation of the direction of the vehicle are included in the computation of the normalized probability. The concept leads to reasonable and applicable results (see paragraph 7.1.2). However, there is still space for improvement.

The IME, as it is presented in this work, computes the probability of performing a certain maneuver mainly based on the position and its standard deviation. The result of the procedure is a collection of assignments of vehicles' positions to geometric representations of its maneuver possibilities. These assignments furthermore include probability values. The assignments are treated independently, meaning that the sum of probabilities of all maneuver possibilities originating from one single approach to the intersection is equal to one. The *Intersection Maneuvers Estimation* determines the probability distributions over a lane. This probability is altered by including different factors that consider additional input values. This is possible for a rather small number of input values. But there are still aspects to be included:

- route advices of the on-board navigation system
- the speed of the approaching vehicle
- turning rates at the intersection
- the type of lane (separate turning lane or mixed lane)

To consider this additional information, the previously mentioned Bayesian Networks could be an appropriate method. It is realistic to ascertain these additional input values, except for the route advice of the on-board navigation system. It is very unlikely that a specific route advice to a driver will be transmitted to the IRS because of privacy issues, although it would be a rather strong argument to estimate future maneuvers at intersections. The speed of the approaching vehicle in combination with the traffic light control could indicate whether a vehicle is likely to turn or to go straight. In case the vehicle travels at a rather slow speed at a green light it might turn and not go straight. The situation is easy to assess if the vehicle is the only one at the interaction, but in case of congestion at the intersection the interpretation of the speed becomes more complicated. In this case the turning rates might be helpful input values because they provide information on the share of vehicles turning left and right, as well as vehicles going straight. This data could be collected automatically by the system and could later also be provided to the traffic light control planners. The information on the type of lane would also be useful as an additional input value, since it is likely that a vehicle on a separate left turning lane will finally turn left. This additional information would also lower the weight of the input value “turn signal”. The turn signal might also be not used by the driver. So, the human-in-the-loop is represented to a rather large extent at this state of the IME.

The estimation of the maneuver is the first step of the collision warning system presented in this work. After the estimation of the maneuver, the actual trajectories need to be predicted. The concept of trajectory prediction is described in the next paragraph.

5 Prediction of the Movement

This section reports on the prediction of the vehicle trajectories. The prediction is based on reference tracks that were introduced in Paragraph 4.2 and the concept of resistance points, which will be explained in detail in this paragraph. The task of the procedure Intersection Movement Approximation (IMA) is to project the route assigned to each vehicle or bicycle entering the intersection onto time steps to gain a trajectory. The section starts with a brief overview of different approaches on prediction of trajectories. In the following the IMA for the vehicle trajectories is outlined. The prediction of the bicycles' trajectories follows an identical concept.

5.1 Estimation of Vehicle Maneuvers and Prediction of Trajectories

Looking at the vehicles' future path is not an easy task. The behavior of a driver and therefore the path a vehicle takes depends on manifold aspects, such as the intention of the driver, the dynamics of the vehicle, the presence of other road users, the topology of the road or intersection, as well as traffic rules and traffic control. Furthermore, the prediction models only consider a subset of the mentioned aspects and abstract them to a certain grade. Also, the models focus on different parts of the “look into the future”. There are methods to anticipate the intention of the driver on a very short term, other methods try to estimate the maneuver the vehicle takes at the intersection, for example, and a variety of methods predict the dynamic state of the vehicle using filter techniques into the near future. In the following segment, some approaches are described to provide an overview of the topic of predicting a vehicle’s future path. What all these methods have in common is that they are used for advanced driver assistance systems on board the vehicle.

SCHUBERT, SCHEUNERT ET AL. [2007] present a sampling-based path planning algorithm. The aim of the algorithm is to identify a path for the vehicle is likely to take based on one configuration state described by its position and orientation to the next configuration state. They propose to start by generating a reachability graph linking the first and the next configuration state. The graph is constructed by applying a maximum and minimum steering angle to the vehicle and also the option to go straight for a certain discrete time. They use polar splines to generate the graph, because these splines model the path of a vehicle more realistically than normal circular arcs. The reason for this simplification is an attempt to reduce the number of possibilities and therefore the search space. To identify a reasonable path, a shortest path algorithm such as Dijkstra or A*-algorithm, considering a special cost function, is used. For the path planning on highways SCHUBERT proposes to take into account the minimum distance and the lane width. This function makes the algorithm aware of obstacles, too. Figure 2.1 depicts the starting position of the vehicle and the next position of the vehicle (green boxes). The black lines represent the constructed graph and the blue line the cost-efficient path which has been identified. Inserting another obstacle (small red box) the system re-plans the path for the vehicle.

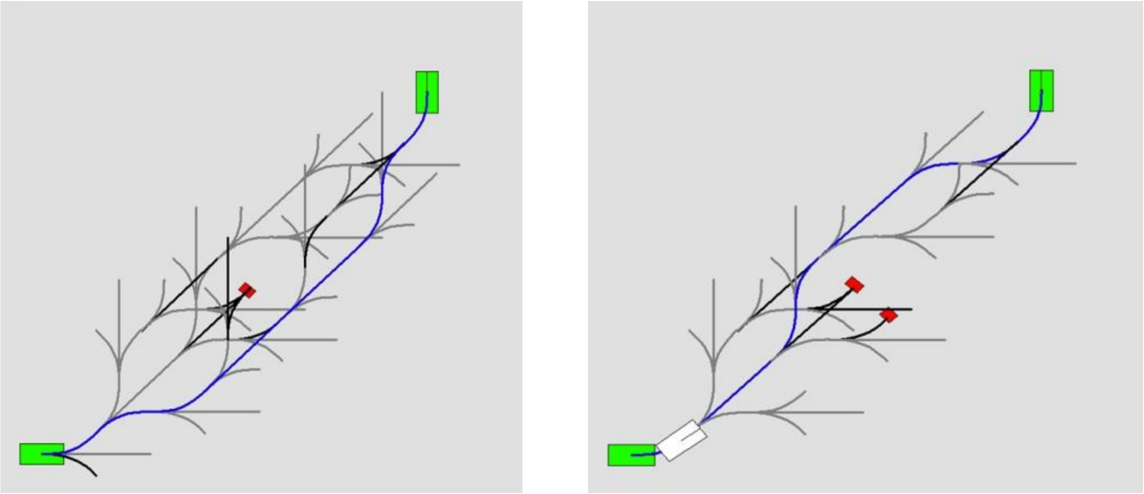


Figure 5.1 Path planning based on polar splines [SCHUBERT, SCHEUNERT ET AL., 2007]

For the highway scenario, this approach is very reasonable. For the construction of the graph in an intersection scenario, the topology of the intersection a more complex cost function considering dynamic information about the vehicle must be taken into account. The goal of the IRIS-System at this state is to estimate the probability of the possible maneuvers a vehicle can take approaching the intersection.

MACEK ET AL. [2006] introduce a motion planning concept for car-like vehicles driving in urban environments. The idea is to plan the future motion of the vehicle in a way that it drives through the scenario without any conflicts with other objects. Like SCHUBERT, he describes the vehicles state using its position, orientation and steering angle. Using the wheel radius, the speed of the vehicle and the steering rate for describing the controllability of the vehicle, he generates a kinematic model. Based on that model, he computes a family of possible B-splines considering the given range of the controllability of the vehicle and obstacle free regions, which results in so-called Rapidly Exploring Trees. These trees consider also the acceleration and the duration of the acceleration of a vehicle. Within the tree he uses Dijkstra for searching the shortest path and smoothing the final path, which is the path the vehicle will take. Just like SCHUBERT'S approach, MACEK'S method is not suitable for the IRIS-System for the highway path planning. His approach is about planning a future path for a vehicle and not determining the likely path or the probability for a certain maneuver a vehicle might take independently from any planning pattern of a system.

SCHNEIDER [2009] presents methods for estimating a driver's intention or a vehicle's future maneuvers. He distinguishes four main methodical categories the approaches for estimating the vehicle's maneuvers can be assigned to: rule-based, probability-based, knowledge-based and iterative methods. For all four procedures, it is customary to deal with uncertain knowledge and information. Rule-based approaches transform vehicles from their current state to the next state using a fixed series of states with predefined conditions for changing the state. Certain conditions will lead to corresponding maneuvers. Using Fuzzy Theory enables researchers to include uncertainty. Fuzzy Theory is also used in the iterative method, as SCHNEIDER reports further. The recognition of the state of a system and connected behavioral decisions, which are based on the system state, are processed iteratively in order to extract the necessary knowledge on the future behavior. Knowledge-based methods try to identify critical situations based on the physical measurement of the vehicles. The algorithm checks whether the possible maneuvers of the vehicles are in conflict to each other. Uncertainty is incorporated by the defining range for the value of the measurements.

Probability-based approaches are able to deal with uncertainties using Bayesian Networks. KJAERULFF ET AL. [2008] define a Bayesian Network *“as an acyclic directed graph which defines a factorization of a joint probability distribution over the variables that are represented by the nodes of the graph, where the factorization is given by the directed links of the graph.”* The links of the graph also depict how the variables relate to each other. Only linked ones are conditional. Furthermore, it is important to mention that there are no cycles in the graph. This avoids the risk of getting stuck in the “chicken-egg problem”. The total number of stochastic variables represents uncertain knowledge and the graph depicts the distribution of that uncertain knowledge. According to SCHNEIDER [2009], Bayesian Networks allow researchers to consider the uncertainties in a driver's awareness in a certain situation and the uncertainties of the sensors providing information.

KLANNER [2008] reports on using Dynamic Bayesian Networks for predicting a driver's intention to turn. A Dynamic Bayesian Network incorporates time-dependent variables to model a time series, such as the behavior of an approaching vehicle. He uses the indicator, the use of the gas pedal, the use of the brake pedal, the suggestion of the onboard navigation system and whether the vehicle is able to stop at the stop line according to a necessary deceleration. For estimating the maneuver of the vehicle this approach is certainly worth to consider for improving IRIS.

ZHANG ET AL. [2009] use Dynamic Bayesian Networks for modeling and predicting the driving behavior of a vehicle approaching an urban intersection, too. According to ZHANG, behavior prediction can be classified into a high-level and a low-level part. The high-level part deals with the modeling of the global maneuver decision of the driver such as turning left or stopping at a red light. At the low-level part, speed profiles are estimated based on the results of the high-level part. His proposed model is a combination of the two parts considering the position of the vehicles, its yaw rate, the indicator state, the velocity and the status of the traffic light. Based on the position, the velocity and the indicator status, the model can deduce the lane. The status of the indicator, the lane the vehicle is assigned to, as well as the status of the traffic lights has just one direct parent in the Dynamic Bayesian Network. This allows researchers to deduce the position and velocity of the current time step from the yaw rate of the previous time step and the assigned lane, traffic light status and indicators status of the current time step.

The work of HERMES ET AL. [2009] presents an approach that could help to predict trajectories for 2 s to 4 s into the future. For the prediction, he uses an archive of acquired vehicle trajectories. In this database, the authors search for the longest common sequence, i.e. a part of the trajectory, of the vehicle's motion history to retrieve a matching trajectory in the database. A typical weight is assigned to each trajectory in the database. Using this weight and the information on the longest common sequence, the authors could predict a likelihood and the motion state of the vehicle to subsequent time steps by using a particle filter. The prediction model of HERMES does not consider traffic lights and other vehicles. KÄFER ET AL. [2010] extend HERMES' prediction approach to recognize situations at intersections without any traffic light control. KÄFER assumes that the vehicles are able to turn right, left and to go straight at these intersections. He introduces a multiple-participant trajectory, which comprises of the yaw rate and the velocities of the vehicles of each predicted trajectory pair. Furthermore, he includes the expected behavior of the drivers trying to avoid collisions by considering the time-to-collision of the two trajectories. His tests with two vehicles showed that the correct situation could be recognized about 1 s to 2 s before the vehicles would collide. Tests with more vehicles have not been conducted yet. Based on the previous work of WIEST ET AL. [2012], a Gaussian Mixture Model was used to define a probability density function for each trajectory. Furthermore, he includes the topology of the intersection using a Hierarchical Mixture of Experts model [WIEST ET AL., 2013].

The reported approaches of maneuver estimation and trajectory prediction are all located on-board a vehicle. The approaches either plan a collision-free path for the vehicle or predicted the motion of the vehicle in the very near future. The motion prediction models rely mostly on information of internal sensors of the vehicle, which provide their data at a high frequency. For the IRIS-System, these preconditions do not hold; the prediction system will not run on-board a vehicle. Furthermore, it should predict the movement of more than one vehicle and it is not able to provide the system with high-frequency internal vehicle data, the amount of different information is smaller compared to on-board systems and the path of a vehicle should not be planned for future movement of the vehicle. Therefore, a new method is proposed in the following.

5.2 Trajectories and Resistance Points

The Intersection Maneuver Estimator (IME) estimates the probability for a vehicle to execute a certain maneuver, i.e. to follow a certain reference track. The reference tracks presented in Paragraph 4.2 are predefined routes to which a vehicle is assigned to. The normalized probability p_{ik}^{norm} for a vehicle i to be on a reference track k that is part of the entry approach h to an intersection is the result of the IME process.

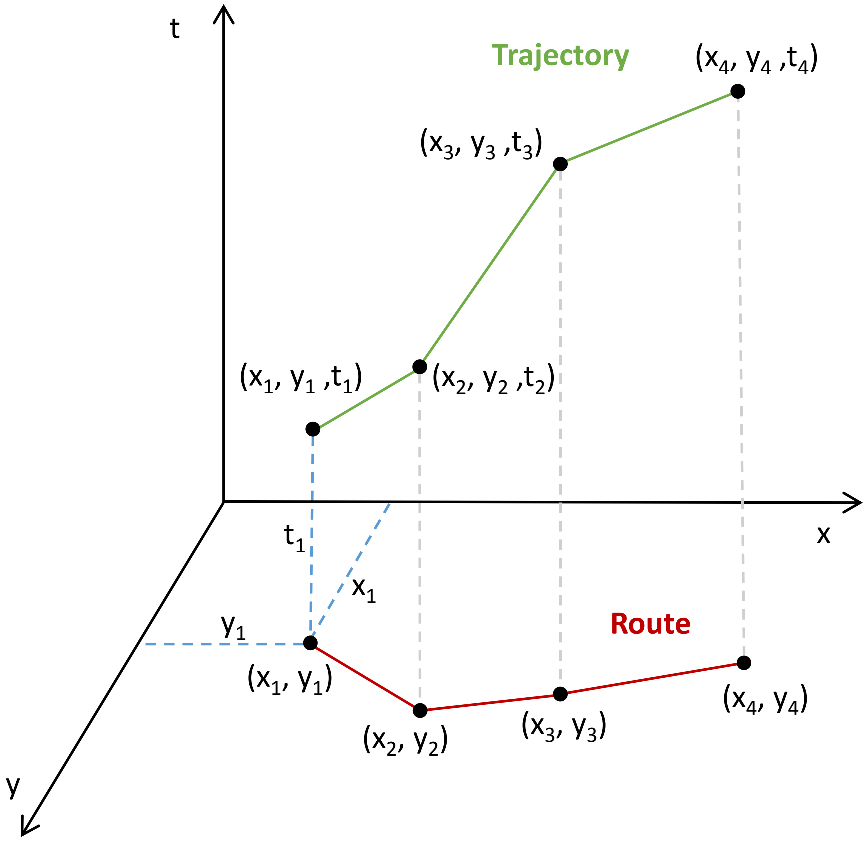
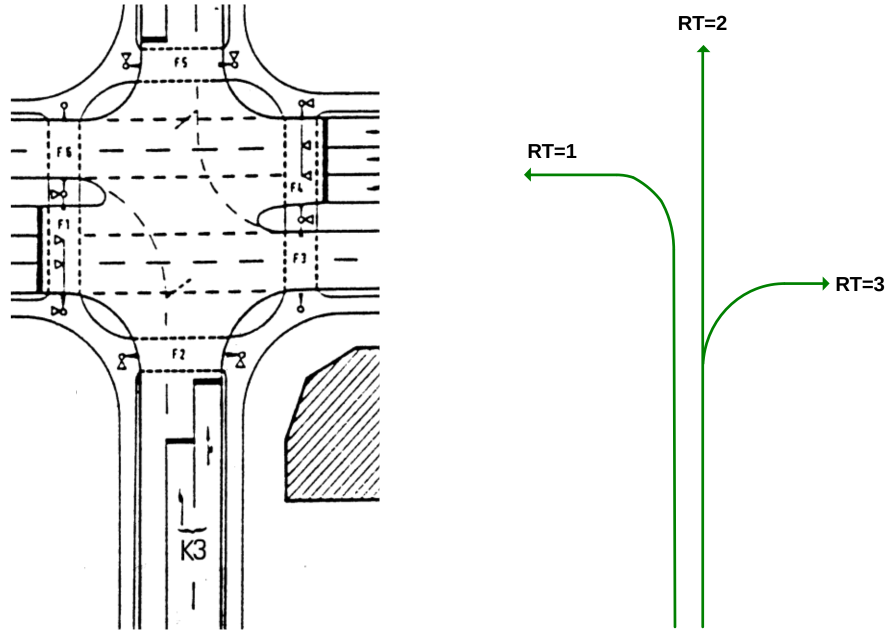


Figure 5.2 Graphical description of route and trajectory

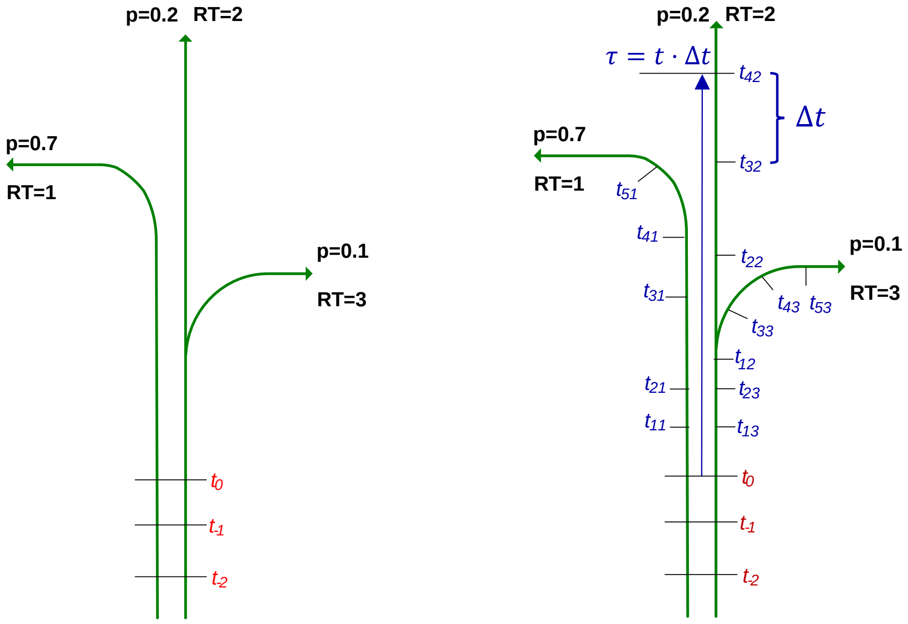
But knowing the probability of a vehicle to choose a certain reference track does not answer the question where this vehicle is located at a certain point in time in the near future. To answer that question, a time component needs to be assigned to the reference track and the route needs to be transferred into a trajectory. According to TRAJCEVSKI ET AL. [2002] *a trajectory of a moving object is a polyline in three-dimensional space (two-dimensional geography, plus time), represented as a sequence of points (x1, y1, t1), (x2, y2, t2), ..., (xn, yn, tn) (t1 < t2 < ... < tn). For a given trajectory, its projection on the X-Y plane is called the route of trajectory.* Figure 5.2 visualizes the distinction between a route (red line) and a trajectory (green line).

The task of the next process step, the *Intersection Movement Approximation (IMA),* is to project the route assigned to each vehicle entering the intersection onto time steps to gain a trajectory. This trajectory is a possible parameterization of the movement. This is realized by time-discrete modeling of the moving objects with a time step t. (Δt = 0.5 s). The prediction horizon T for the prediction is 5 s.



Plan of Intersection

Reference Tracks



RTs and Probability

Probability and Prediction

Figure 5.3 Reference tracks, estimated maneuvers and predicted trajectories for on intersection approach

Figure 5.3 depicts this understanding based on a simple example. The vehicle is in at the stop line of an intersection and has three routes to which the vehicle is assigned to with a certain probability. On the left, there is the blue print of the intersection, the second picture shows the reference tracks according to the maneuver possibilities, the third picture visualizes red time stamps which indicate the past until the starting point t_0 of the prediction and the estimated probabilities. The last picture finally shows the short-term prediction of the trajectory marked blue. The length of one prediction step in time is Δt, the number of the prediction step is t and the prediction time into the future is $\tau = t \cdot \Delta t$.

It is obvious that vehicles do not move independently from other road users. They have to ensure a certain lateral and longitudinal clearance from each other in order to avoid perilous situations. Furthermore, traffic rules and the local traffic control facilities, such as traffic lights, influence the behavior of road users and guide them through traffic situations. Surrounding traffic consequently has to be taken into account in the approximation of possible movements. Therefore, the prediction needs to consider some basic presumptions, which are expressed in the following four rules:

- The prediction tries to be in line with traffic rules as much as possible (depending on the movement status of the vehicle at the current time point t_0).
- Movements of vehicles are assumed to be physically reasonable, e.g. deceleration before turning.
- The model does not consider cross-correlations of vehicles on different reference tracks; i.e. the movements of two different vehicles on two different reference tracks are independent from each other. The reason for this restriction is to reduce algorithmic complexity.
- However, the model considers cross-correlations of the movement approximation of vehicles which are on the same reference tracks to model the car following behavior in a simplified way.

The concept of the *resistance points* (RP) is used to model interdependencies and to obey the rules laid out above [SCHENDZIELORZ ET AL., 2014]. Each RP is located on at least one reference track. RPs are assigned to four different categories as listed in Table 5.1.

As shown in Table 5.1, the first three RPs are *fixed resistance points* (FRP) on the reference tracks. These FRPs are independent from any traffic situation. Their position only relies on the topographical representation of the intersection through the reference tracks. The fourth RP is a *moving resistance point (MRP)* representing the presence of other vehicles on the same RT. All *RPs* are points on the RT polyline. They are characterized by the following three attributes: position of the RP, *required speed* v^{req} and *driver awareness distance* d^{aw}. The dynamic value required speed v^{req} introduces an obligatory speed at a certain point of the trajectory (the RP location) that a vehicle must attain to comply with applicable traffic rules or to move reasonably. For instance, a RP at the stop line requires a speed of zero if the traffic light is red. The static spatial driver awareness distance d^{aw} describes the perception horizon of the driver with respect to the circumstances involved with the RP. This is since the trajectory prediction has to consider the RPs from the point in time when the driver must be aware of the traffic situation expressed through the RP. The default driver awareness distance is set to 50 m.

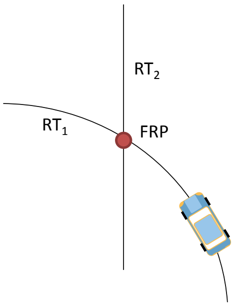
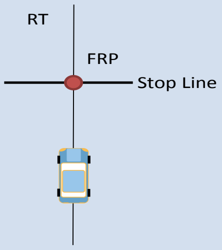
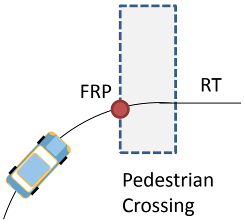
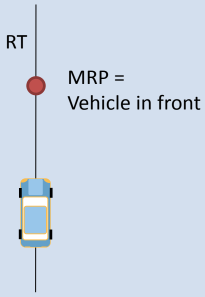
Fixed Resistance Point (FRP) referring to the intersection of conflicting reference tracks	
Fixed Resistance Point (FRP) referring to the intersection of reference track and traffic light stop line	
Fixed Resistance Point (FRP) referring to the intersection of a reference track and conflicting pedestrian crossing	
Moving Resistance Point (MRP) referring to the possible location of other vehicles ahead	

Table 5.1 Categories of resistance points [SCHENDZIELORZ ET AL., 2014]

5.3 Generation of the Resistance Points

5.3.1 Location of the Resistance Points

Before running the trajectory prediction, the fixed resistance points need to be computed. In order to create these RPs, the *Intersection Movement Approximation* first checks all reference tracks. If the RT represents a left or a right turn, the RTs are checked a second time. If the second RT is not identical to the first one and if the second RT represents a straight movement throughout the crossing, the intercept point (=FRP) of the two RTs is computed. This procedure computes the FRPs that are required for the case *“right turning vehicle and bicycle”* and *“unprotected left turning vehicle”*. Furthermore, it assures that no useless RPs are created. In order to cover more scenarios, such as two vehicles crossing rectangular to each other, the corresponding RPs need to be computed. This was not done in this case, so therefore the IRIS-System in its current configuration state is not able to cope with that kind of scenarios. A similar approach holds for the computation of the FRP necessary for the scenarios *“red light violation”* and *“pedestrian warning”*. They are derived from the intersection of a RT and a stop line, as well as a RT and the first intersection of the geometric representation of the pedestrian crossing.

After having created all fixed resistant points, the next step is the computation of the moving resistant points. As each single vehicle is a possible MRP for other vehicles behind that move on the same RT, the positions of the vehicles are converted to MRPs. Therefore, all detected moving objects are checked for being a vehicle or a bicycle. For further calculations, the latest position measurement of the moving object is considered. Next, the process collects the results of the pre-executed maneuver estimation to extract information about the moving object. The position of the MRP is determined if

- the object is assigned to a reference track,
- the longitudinal offset on the reference track is larger than zero, otherwise the moving object is right about to enter the area of interest,
- and the normalized probability p_{ik}^{norm} is larger than a pre-defined threshold.

A RP is located on a RT, but the position of the vehicle or bicycle does not necessarily lie on a RT. Therefore, the position of the object needs to be projected orthogonally onto the nearest RT. The resulting point is the MRP of the vehicle or bicycle. The MPR, which is derived from the true position of the moving object *i* by projection on RT, also represents the starting point $z_{ikt}\ (t = 0)$ of the predicted trajectory of that object. Additionally, further attributes such as the normalized probability p_{ik}^{norm}, which is taken to be constant during the IMA, the maximum acceleration a^{max} and the current speed v_{ikt} are assigned to the MRP.

5.3.2 Required Speed of the Resistance Points

The resistance points of the reference tracks can be regarded as frame conditions for the movement prediction of any vehicle on the track. To structure these conditions, three rules have been defined. The priority of these rules is increasing, i.e., rule 3 overrules rule 2 and rule 2 overrules rule 1. The rules for the reference tracks and the resistance points influence the vehicle movement in the following way:

1) Every vehicle tries to stay in line with the typical speed of each reference track segment (for definition of typical speed see page 51).
2) Every vehicle tries to get in line with the required speed of the next FRP (when it reaches its location) as soon as it enters the driver awareness area defined by the driver awareness distance. If possible, it will ensure this compliance with most convenient acceleration or deceleration maneuvers.
3) Every vehicle tries to get in line with the required speed of the next MRP as soon as it enters the driver awareness area. If possible, it will ensure this compliance with most convenient acceleration or deceleration maneuvers.

Location/Situation	**Comments**	**Required Speed**
1. Pedestrian Crossing – red	The light is red for pedestrians	8.5 m/s
2. Pedestrian Crossing – green – pedestrians present	The vehicle is turning, the light is green for pedestrians and pedestrians have been detected.	0 m/s
3. Pedestrian Crossing – green – right turn – no pedestrians present	The vehicle is turning right, the light is green for pedestrians no pedestrians have been detected.	4.0 m/s
4. Pedestrian Crossing – green – left turn - no pedestrians present	Same as in point 3, because the vehicle will accelerate more to clear the intersection and is able to turn at a higher speed because of the larger radius than at the right turn	8.0 m/s
5. Stop Line – green – straight direction	Vehicle intends to cross	Equation (5.2)
6. Stop Line – green – left direction	Vehicle intends to turn left	Equation (5.3)
7. Stop Line – green – right direction	Vehicle intends to turn right	Equation (5.4)
8. Stop Line – red	Vehicle must stop at the red light	Equation (5.5)
9. Conflicting RT	Two vehicles on conflicting RT within distance d_{ik}^{r} from RP and speed v_{ik}	Equation (5.6)
10. Vehicle ahead on the same RT	This depends strongly on the "*driver awareness distance*"	Equation (5.7)

Table 5.2 Overview of the required speed for the resistance points

As all pre-calculations are finished, the main loop for predicting the trajectories over the prediction horizon T though the single prediction steps t starts. Up to that point, the procedure considers neither the presence of pedestrians at the crossings, nor the status of the traffic lights. In total, there are 10 different instructions for computing the required speed. Those are necessary for influencing the predicted movement of the vehicle. Table 5.2 summarizes the concepts for determining the required speed values, which are explained in more detail in the following.

Required Speed of the FRPs Referring to Pedestrian Crossings

This type of FRPs deals with situations in which a vehicle has already passed the stop line and intends to turn right. The system differentiates whether the lights for the pedestrians are green or not and whether the vehicle wants to turn left or right. The last decision point considers the presence of pedestrians. The status of the pedestrian traffic lights at the beginning of the prediction is valid for the whole prediction horizon. If there is no pedestrian present at the crossing and the lights for the pedestrians are red, the vehicle attempts to get in line with the typical speed if there is no other resistance point ahead. Figure 5.4 shows the completed decision process and the assigned values to the required speed by means of a Nassi–Shneiderman diagram (NSD). In the beginning of the calculation process the required speed values have to be estimated because no traffic observations to extract real values were available.

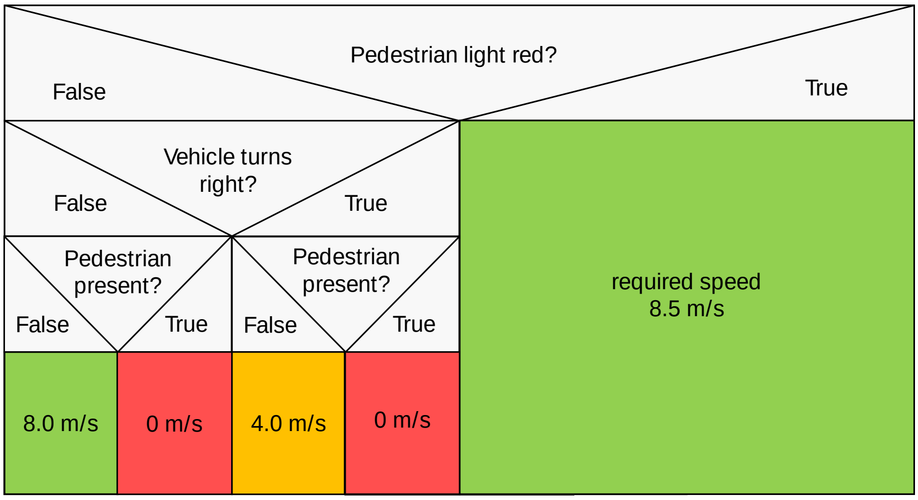


Figure 5.4 NSD for deriving the required speed for the FRP of pedestrian crossings

Required Speed of the FRPs Referring to Stop Lines

The next important FRP are the ones originating from the stop lines at intersections. For this type of FRPs the current and the future status of the traffic lights needs to be considered. The traffic light controller provides the system with the colors as well as the maximum t_{max}^{res} and minimum residual time t_{min}^{res} for each color. This is important in case the system is installed at an intersection with adaptive traffic light control. In contrast to the FRP for the pedestrian crossing, this RP takes into account the current and future traffic light status at each prediction step. Based on the residual times of the traffic light status and the current prediction time into future τ, a residual probability p^{res} can be estimated. The residual probability is the estimated probability that the light will not change and stay at the current color. The current prediction time into future τ is defined as $\tau = t \cdot \Delta t$ and $\tau \leq T$ with T being the prediction horizon. If τ is smaller than the minimum residual time or equal to t_{min}^{res}, the color will not change and therefore the residual probability is set to one. If τ is larger than the minimum residual time but smaller than the maximum residual time, the residual probability is estimated according to equation (5.1). If τ is larger or equal to the maximum residual time the current color just elapsed and the next color, which is known from the traffic light control, will occur. Therefore, the residual probability for the current color is zero.

$$p^{res} = \frac{\tau - t_{min}^{res}}{t_{max}^{res} - t_{min}^{res}} \qquad for \;\; t_{min}^{res} < \tau < t_{max}^{res} \tag{5.1}$$

For modelling the required speed of the RP at the stop line four scenarios are considered:

- vehicle approaches at red
- vehicle goes straight across the intersection at green
- vehicle turns left at green and
- vehicle turns right at green.

Approaching at Red

If the vehicle approaches the stop line on red traffic lights, the residual probability is considered for adapting the required speed according to equation (5.2). In case the traffic light is red for sure ($p^{res} = 1$), the required speed is zero. Otherwise, the smaller the residual probability, the closer the required speed will be to the typical speed:

$$v_{ikt}^{req,r} = (1 - p^{res})^2 \cdot v_k^{typ} \tag{5.2}$$

The three remaining scenarios to be distinguished for estimating the required speed in case the traffic light is not red. These scenarios consider the estimated maneuver of the vehicle and the residual probability.

Straight Direction at Green

According to the RiLSA [FGSV, 2010], a vehicle crosses the street at a speed which is slightly smaller than the speed limit. For 50 km/h in the urban area, the entering speed is 40 km/h. This is an average value. Maximum and minimum acceleration are set for the computation of the acceleration required for getting in line with the “required speed”; no unrealistic values are possible. Therefore, not an average speed value as in the RiLSA should be set, but a more realistic maximum speed at the intersection; considering also occasional speeding. Therefore, the equation (5.3) includes the factor 1.1 to account for the assumption that the vehicles cross the intersection at a 10% higher speed than the legal speed limit in case no other vehicles are present at the intersection.

$$v_{ikt}^{req,r} = p^{res} \cdot v_k^{typ} \cdot 1.10 \tag{5.3}$$

Turning Left at Green

This parameter sets the speed at which a vehicle usually turns left at intersection, if there are no obstructions. The RiLSA proposes a clearing speed of 7 m/s for large curves (radius>10 m). This value has a more defensive character. The lower the clearing speed, the longer the vehicle is in the critical area at the intersection. However, the FRP is located at the stop line before the vehicle starts turning. Therefore, and because the way to the real turn is relatively long, the speed is set to be 12 m/s. The factor $0.86 \approx 12/13.9$ in equation (5.4) expresses this speed reduction before a left turn in relation to the typical speed. In case of 50 km/h, this results in a required speed of 43.2 km/h.

$$v_{ikt}^{req,r} = p^{res} \cdot v_k^{typ} \cdot 0.86 \tag{5.4}$$

Turning Right at Green

The RiLSA proposes a smaller value for curves with a radius < 10 m. which is 5 m/s. Because the way to the real turn is shorter than for turning left and the radius of a right turn normally is smaller than the radius for a left turn, the typical speed needs to be reduced. It is assumed, that the turning speed is about 10 m/s. The factor $0.72 \approx 10/13.9$ in equation (5.5) expresses this speed reduction before a right turn in relation to the typical speed. If this is 50 km/h, the result is a required speed of 36 km/h.

$$v_{ikt}^{req,r} = p^{res} \cdot v_k^{typ} \cdot 0.72 \tag{5.5}$$

The factors for adapting the typical speed are based on assumptions. The factors need to be configured for each intersection IRIS is running on to achieve realistic values. This could either be done by speed observations before installing the system or implementing a kind of self-learning procedure analyzing the speed values the vehicle has while passing the intersection. It is suggesting combining the analysis of the speed profiles with the analysis of the paths of vehicles obtaining reference tracks as proposed in paragraph 4.2.

Figure 5.5 provides an overview of the whole logic. For the scenarios approaching at green only the factors of equations (5.2) to (5.4) are mentioned.

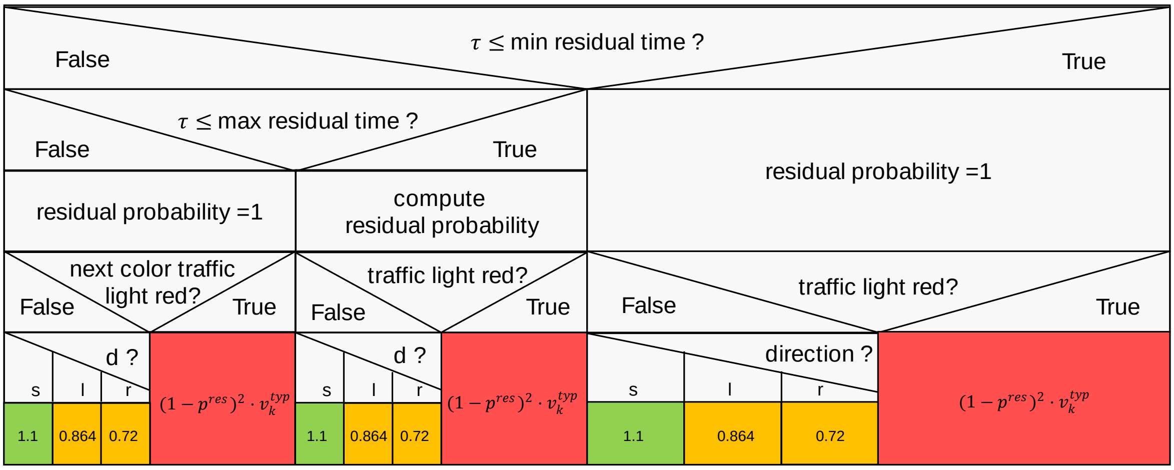


Figure 5.5 NSD for deriving the required speed for the FRP of stop line

A further important aspect to mention is the "dilemma zone" or "indecision zone" in which the driver approaches the intersection while the lights are red/amber. This was not taken into account in the aforementioned list determining the required speed. As already stated a detailed analysis of driver behavior needs to be done to properly model the required speed. To cross the intersection, before the lights turn red, some drivers will increase their speed extraordinarily and some will behave more defensively. According to Gates et al. [2010], who did intensive research on the behavior of approaching vehicles at 6 intersections in Wisconsin (USA), the dilemma zone exists between 2.5 s and 5.5 s upstream of the intersection at the start of the amber interval. This is exactly the prediction horizon of the IRIS-System. In order to gain more knowledge on the behavior of drivers in the dilemma zone, Rakha et al. [2008] performed a driving simulator test. One result of his study is that the dilemma zone of older drivers (≥ 65 years of age) is wider, ranging from a time of 4.81 s to 1.66 s to the stop line versus 4.90 s to 2.87 s for the dilemma zone of younger age group. Female drivers are more likely to stop than male drivers and tend to have a dilemma zone that is closer to the intersection. Truck drivers are more likely to violate red lights, i.e. they decide not to decelerate within the dilemma zone. These results show that it is not an easy task to include the behavior of drivers in a system that is not running on-board a vehicle itself. Therefore, this issue is out of scope for this thesis.

Required Speed of the FRP Referring to RT Intersections

The last value to be computed is the required speed that needs to be assigned to vehicles approaching the FRPs that result from the intersection of two RTs. The location of this RP is fixed, but the required speed assigned to it is not. The case an oncoming vehicle is situated right before the RP the required speed is zero, but the required speed is higher when the vehicle is further away and travelling at a low speed. Therefore, the required speed is the result of a function of the distance to the FRP d_{ik}^r, the current speed of the oncoming vehicle closest to the FRP v_{ik} and the typical speed of the intersecting reference track. The equation below shows the applied function:

$$v_{ikt}^{req,r} = \frac{v_{RT\_intersecting}^{typ}}{1+e^{\left(\alpha-\beta\frac{d_{ik}^{r}}{d_{max}}\right)}} \cdot \sqrt{1-\frac{v_{ik}}{v_{RT\_intersecting}^{typ}}}, \tag{5.6}$$

with the parameters α and β to adjust the function, the maximum awareness distance $d_{max} = 60\ m$ for vehicles and $30\ m$ for bicycles and $v_{RT\_intersecting}^{typ}$ the typical speed of the intersecting reference tracks. The function comprises two parts: the first part computes an initial required speed as a function of the distance of the oncoming intersecting vehicle to the FRP. This is an e-function which can be adjusted by using the parameters α and β; the smaller α is, the steeper the curve will be at smaller distances (compare Figure 5.6 a) and b)); the larger β is, the steeper and the more S-shaped the curve will be (compare Figure 5.6 b) and c)). The figure below illustrates the first part of function (5.6) with d_{ik}^{r} as variables and the typical speed of $50\ km/h$ for both RTs and $d_{max} = 60\ m$. It is obvious that the larger the distance, the higher the required speed and the closer the vehicle is to the FRP, the smaller the required speed should be.

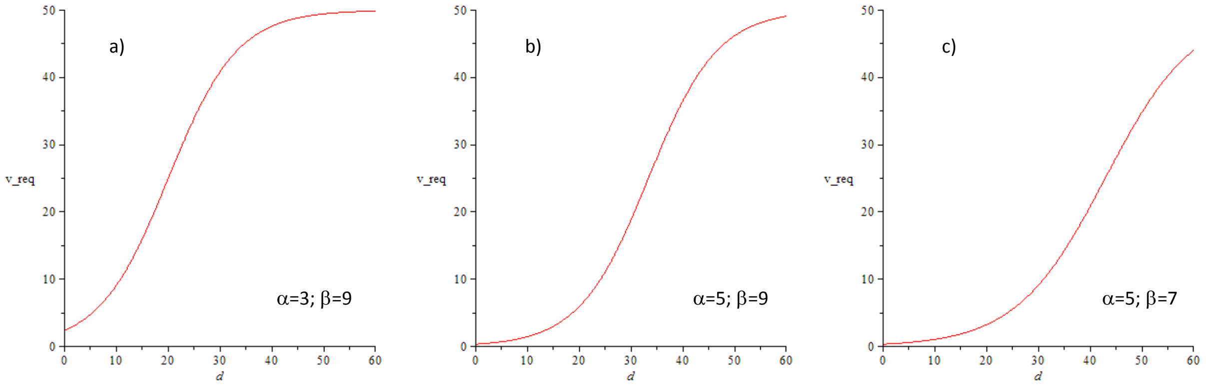


Figure 5.6 E-function to express the dependency of the required speed to the distance to the FRP

The second part of the function is a factor that considers the current speed of the oncoming vehicle or bike. This factor reduces the value of the required speed, i.e. the conditions for braking are harder if the vehicle travels at a high speed. Figure 5.7 depicts the function with a typical speed of $50\ km/h$.

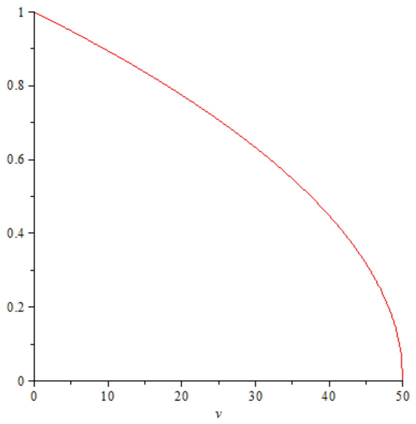


Figure 5.7 Reduction factor for the required speed to consider current speed

Using this concept, the behavior of two vehicles or one vehicle and one bicycle approaching on two different intersection reference tracks is not directly influenced by each other. Therefore, the concept is still in line with the prediction rules stated at page 66. However, the resistance points help to consider this situation without increasing the model's complexity.

Required Speed of the MRP

The situation of one vehicle following another vehicle on the same reference track is modeled by means of moving resistance points. The location of the MRP is determined by the position of the two vehicles. In the case the driver is within awareness distance, the MRP influences the prediction and the required speed is the minimum of the speed of the vehicle in front or the typical speed of the reference track as noted by equation (5.7). This approach represents a simple car following model:

$$v_{ikt}^{req,r} = \min(v_{i-1kt}^{typ}, v_{k}^{typ}). \tag{5.7}$$

5.4 Approximation of the Trajectories

After having determined the required speed values of the resistance points, the approximation of the trajectories of the vehicles and bicycles is the next step. All reference tracks and all vehicles, that the system is aware of, must be considered and the resistance points coming up next to each vehicle need to be identified. A unique representation of a vehicle in the IRIS-System consists of the pair <vehicle i and reference track k>, because the same vehicle can be assigned to different reference tracks with different probabilities.

In case the next resistance point is a fixed one, the probability is checked against a certain threshold. If this probability value is lower than the threshold, this representation is neglected. This is done for the FRPs resulting from the intersection of two RTs, the intersection of a RT and a pedestrian crossing. Only for the FRPs resulting from the stop line there is no probability check. This is since the reference tracks represent the straight crossing at the approach of the intersection. The left turning and the right turning are partly overlapping, but the normalized probability p_{ik}^{norm} can be different. However, each vehicle entering the intersection needs to cross the stop line regardless of where it wants to go. Then the distance d_{ikt}^{r} of the vehicle i on the reference track k at the time t to the RP r is computed for all remaining representations. If this distance is larger than zero and the RP is within the driver awareness distance, this RP is taken into consideration.

The MRPs are computed in a similar way, but there is also no probability check in the beginning. For each vehicle, the normalized probability is computed and the sum of the probabilities of all representations of the same vehicle is 1. However, the reference tracks overlap in the approach of the intersection, and consequently the probabilities of the overlapping RTs of the same vehicle need to be summarized as described in equation (5.8).

$$p_{ih}^{norm} = \sum_{k \in \kappa} p_{ik}^{norm} \quad \forall i, k \in \mathcal{H}, \mathcal{H} \in \mathcal{K} \,, \tag{5.8}$$

with the set of all reference tracks $\mathcal{K}$ and the set of all overlapping reference tracks in one single approach of the intersection $\mathcal{H}$. For each vehicle on a certain reference track the influence of all the other vehicles which are on the same reference tracks are checked. If the distance d_{ikt}^{r} of the vehicle i to a MRP is larger than zero and $d_{ikt}^{r} < d^{aw}$, the MRP is considered to be ahead of the vehicle and therefore it needs to be taken into account. The required speed for the vehicle i is the minimum of the current speed of the MRP and the typical speed at the reference track.

The required acceleration $a_{ikt}^{req,r}$ for each vehicle i on a reference track k in each time step for all resistance points r within the awareness distance is computed according to equation (5.9) based on the speed of a vehicle v_{ikt}, the required speed of a resistance point $v_{ikt}^{req,r}$, the distance to a RP d_{ikt}^{r} and the vehicle length l. The length l of half the vehicle is subtracted from the distance to the RP to consider the dimensions of the vehicle as the moving objects are treated like single points describing their geometric center. The vehicle length is a static parameter and is set to 4 m.

$$a_{ikt}^{req,r} = 0.5 \cdot \frac{(v_{ikt})^2 - \left(v_{ikt}^{req,r}\right)^2}{d_{ikt}^{r} - 0.5 \cdot l} \quad \forall i, k, r, t \tag{5.9}$$

As equation (5.9) is executed for all prediction time steps t and different resistance points, it is not clear which acceleration shall be assigned to the vehicle. To determine the relevant acceleration for the vehicle i on the track k two cases need to be differentiated with $a_{ikt}^{req,r}$ being either positive or negative. Or, in other words, the resistance point causes the vehicle to either accelerate or to decelerate. Furthermore, the capabilities of the vehicle to accelerate and decelerate need to be considered to avoid any unrealistic behavior resulting in unrealistic trajectories. To select the final acceleration, the deceleration overrules the acceleration. Equation (5.10) reflects the logic of choosing the appropriate acceleration and deceleration.

$$a_{ikt}^{req} := \begin{array}{ll} \max\left(\min_{r}(a_{ikt}^{req,r}), a_{min}\right), & a_{ikt}^{req,r} \in k < 0 \\ \min\left(\max_{r}(a_{ikt}^{req,r}), a_{max}\right), & a_{ikt}^{req,r} \in k \geq 0 \end{array} \quad \forall i, k, r \tag{5.10}$$

where a_{max} is the maximum acceleration of the vehicle and a_{min} is the minimum acceleration (deceleration), considering the acceleration capabilities of the vehicle. These two parameters are fixed and identical for all vehicles. It is obvious that the acceleration parameters are not fixed in real vehicles. Their values depend on the driver characteristics, the type of vehicle, the friction of the road surface and the intended driving maneuver. As BURG [2009] reports on page 378ff, the maximum acceleration with 4 m/s² is the upper limit of the values for acceleration behavior considering different driving maneuvers. For the deceleration 3 m/s² reflects a comfortable braking maneuver, according to MAURER [2012]. According to BREUER [2012] the average deceleration value for vehicles travelling at 50 km/h is about -5.5 m/s² and the maximum is about -8 m/s². As the system only deals with normal passenger cars and the fixed acceleration parameters set the boundaries for the acceleration behavior of the vehicles, the maximum acceleration is set to 4 m/s² and the maximum deceleration is set to 8 m/s².

With the required acceleration determined the distance the vehicle moves during the next time step $t+1$ is provided by equation (5.11) with Δt being the size of the prediction step in time:

$$d_{i,k,t+1} = v_{ikt} \cdot \Delta t + 0.5 \cdot a_{ikt}^{req} \cdot \Delta t^2 \tag{5.11}$$

Based on the distance $d_{i,k,t+1}$, the system computes the new position $z_{i,k,t+1}$ of the vehicle i on the reference track k. The procedure closes with the determination of the new speed of the vehicle following equation (5.12).

$$v_{i,k,t+1} = v_{i,k,t} + a_{i,k,t}^{req} \cdot \Delta t \tag{5.12}$$

It should be noted at this point, that the time the prediction procedure takes to be executed is neglected by computing the new distance of the vehicle at the current state of the system development. This vehicle might run a certain small distance during this processing time. This provides space for improving the IRIS-System in future. Some measurements on the used processing time need to be done to exhaust this potential.

Figure 5.8 depicts an overview of the *Intersection Movement Approximation* algorithm. The Nassi–Shneiderman diagram indicates that for each time step t, each reference track k and all vehicles i on a track it is first checked, whether a fixed resistance point is within the range of the driver awareness distance. Second, it is checked, whether there is a moving resistant point in range. According to the frame conditions of each RP, the required acceleration is computed and the trajectory is approximated. The result of the estimation of the vehicle's maneuver and the prediction of its trajectory is a bundle of maneuvers with a certain probability and the computation of the positions and speed of the vehicle on the reference track.

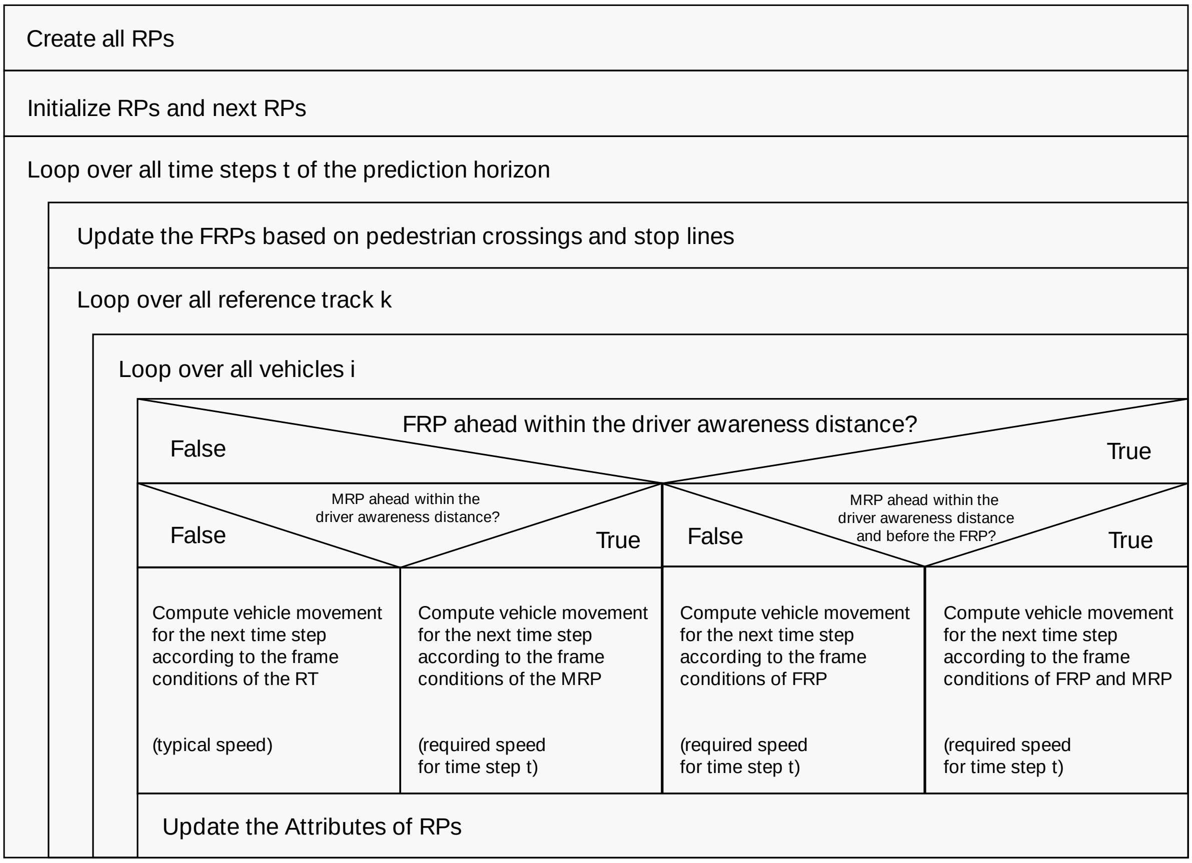


Figure 5.8 NSD of the movement approximation algorithm [SCHENDZIELORZ ET AL., 2014]

The estimation of the speed of the presented trajectory prediction relies mainly on the required speed of the resistance points the vehicle is driving on. The position is influenced by the shape of the reference tracks. As already stated in paragraph 4.2 referring to ALHAJYASEEN ET AL. [2011] or EICHHORN ET AL. [2013], the track a vehicle describes while turning or crossing an intersection is not a single line but more a family of tracks. To improve the validity of the reference tracks, the tracks of the vehicles passing by could be stored, evaluated afterwards and the RTs adjusted using ALHAJYASEEN'S or EICHHORN'S approach. But this is only possible when the system is installed at an intersection for a longer period. For the estimates of speed historic data can be evaluated as well. However, BERNDT ET AL. [2007] report that statistical tests have shown that the velocity distribution of different drivers approaching an intersection is not a normal distribution. As the IRIS-System does not receive any information about the driver, it is quite a challenge to improve the estimation of the speed based on historic data without any additional information such as more kinematic data of the vehicle.

Aside from this possibility of improvement, the estimated maneuver probability and the predicted trajectory of the vehicles are the input for executing the remaining step - the threat assessment. The following paragraph describes how the situation is assessed and how a final decision on issuing a warning or not is made.

6 Threat Assessment of the Situation

Once the maneuvers have been estimated and the trajectories predicted, the evolving situation needs to be assessed to decide whether there is a risk of a traffic conflict or not. For assessing trajectories of moving objects such as cars, traffic conflict techniques (TCT) are a widely known approach. Therefore, the following chapter introduces the idea of TCT and gives an overview on common measures. The approach chosen for the IRIS-System is explained afterwards. The chapter closes with some aspects of the driver reaction time and behavior.

6.1 Origin and Overview of Traffic Conflict Techniques

Based on the description of the future situation at an intersection, a method for identifying potential conflicts needs to be defined. The immediate question is how to define conflicting situations in traffic. According to HORST [1990], the so-called traffic conflict technique (TCT) was introduced in the late 1960’s to fill a need for identifying safety problems related to vehicle construction. He further reports that Perkins and Harris (1967) define a traffic conflict “as any potential accident situation, leading to the occurrence of evasive actions such as braking and swerving.” They identified these unsafe interactions between vehicles by observing the flashing of brake lights and lane changes.

The observation by humans has two main drawbacks. Firstly, a collision might occur without any countermeasure before. Secondly, without intensive training of the observing personal it is not possible to identify the severity of the conflict, HORST continues. Using camera video analysis of the traffic situation mainly at intersections it was possible to support the human observers, as e.g. ERKE ET AL. [1985] and HUPFER [1997] state. This also leads to a more precise definition of a conflict formulated by Hyden (1987): “A conflict is either an event that would have led to a collision if both road-users had continued with unchanged speeds and directions or a near-miss situation where at least one of the road-users acts as if they were on a collision course”, as MALKHAMAH ET AL. [2005] report.

TCT is not only used in real traffic observations, but also in microscopic traffic simulations. The advantage of microscopic traffic simulation is that all the necessary data, the vehicle trajectories, for computing the TCT measure are available, as reported by ARCHER [2005] and GETTMAN ET AL. [2003]. Based on the use of TCT in microscopic traffic simulations CUNTO ET AL. [2006] adapt the definition of a traffic conflict as follows “A traffic conflict is defined as a juxtaposition of vehicle trajectories (more than one vehicle occupying the same space at the same time).”

Anything related to a traffic conflict, be it the vehicle’s acceleration, the amount of time a driver must react before an accident or the time between vehicle crossings at an intersection, can be considered as a measure for the TCT as long as it is used in a way, which either analyzes or helps to identify traffic conflicts. While the measures described in the following are the ones most frequently used by engineers and scientists, there is by no means a limit to the number or types of measures that may be used. As for their use, measures of the TCT are sometimes very versatile, while some can only be applied to one specific situation.

Time to Collision (TTC) is the most common known TCT measure. It measures the amount of time left until a vehicle would collide with another object, assuming that no change in velocity would be made by either the vehicle or the object. It is used in a variety of situations, ranging from car-following scenarios to intersection crossings to approaching a stationary object. It is quantified by dividing the headway distance by the relative velocity of the two objects in question. Because the time to collision must be a positive number, relative velocity must also be positive. Thus, TTC is only valid if the following vehicle has a greater velocity than the object in front of it. The disadvantage of TTC is that the TTC value theoretically reaches infinity when a vehicle follows at the same speed as the vehicle ahead. Even if they were driving quite close behind one another, the TTC would not indicate this as a critical situation. Another drawback is that the TTC normally only operates in the case both vehicles are travelling along the same path.

ALLEN ET AL. [1978] were aware of those issues and therefore he presented six TCT measures to be applied specifically at intersections. The first measure he proposed was the **Proportion of Stopping Distance (PSD).** This is the ratio of the distance available for a vehicle to make a maneuver to the necessary braking distance to a set point. In terms of traffic safety, the set point would be a point of collision. If the ratio is greater than 1, a collision is not imminent; a ratio of less than 1, though, indicates a collision situation. That means that a PSD value of 0.50 would mean that the driver would have only half the acceptable minimum stopping distance at a chosen maximum deceleration rate, whereas a PSD value of 1.0 or more would be needed to stop safely before the expected collision point.

Gap Time (GT) is used to describe a conflict event in the initial stage of development, described by the dotted line (1) in Figure 6.1. This figure describes a time-distance diagram of a vehicle driving straight through an intersection and a crossing vehicle. The driver going straight would perceive a potential collision with the crossing vehicle. Line (1) describes this exception; the vehicle will maintain the approach speed. The GT value is equal to the time between the completion of an interference of another vehicle and the arrival of the conflicted vehicle, assuming that both do not change their speeds. If the driver going straight is expecting the gap time as being too short to cross safely, he/she will take evasive action in terms of braking at time point T2. After succeeding in avoiding the collision, the driver will attempt to recover his/her previous driving speed by acceleration. This is represented by line (2). If the driver had not accelerated after the encroachment, he/she would continue at a lower speed, as line (3) describes. In their work GETTMAN ET AL. [2003] refer to the GT as TTC, meaning the time the vehicle needs to reach the conflict point based on the initial stage.

The second measure, the **Initial Deceleration Rate (IDR),** is simply the rate at which a vehicle decreases its velocity at the point in time starting with evasive or braking action to avoid the collision. In the example of Figure 6.1 this is at T2. The IDR varies from driver to driver. However, rapid declaration will generally indicate a severe situation, whereas moderate declaration normally implies a less severe situation.

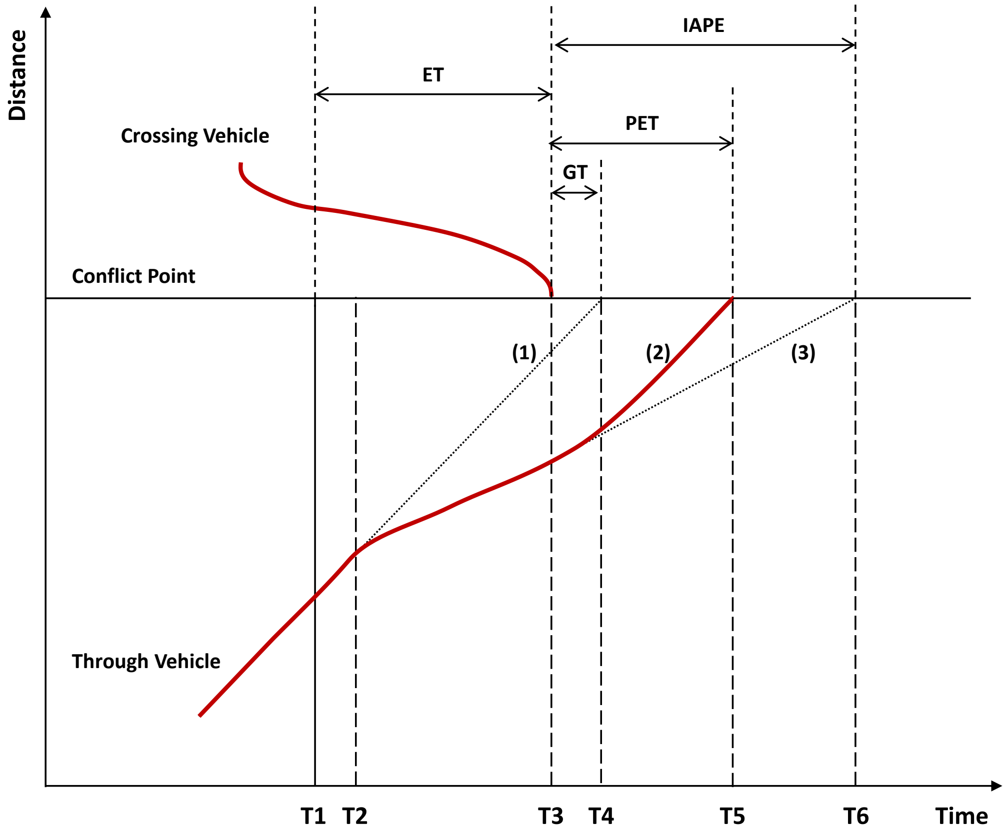


Figure 6.1 TCT measures on conflict point time-distance diagram referring to [Allen et al., 1978] and [Gettman et al., 2003]

As a third measure Allen proposed **Encroachment Time (ET)**. The ET is the time duration in which a vehicle enters and stays in a potential conflict area with another vehicle. That means at T1 the though vehicle perceives a potential conflict with the crossing vehicle. The end of ET duration marks the beginning of measurements for post-encroachment time. The **Post-Encroachment Time (PET)** is used when one vehicle crosses the path of another. The PET measures the time difference between departure of the offending vehicle and arrival of the conflicted vehicle at the point of the conflict. Therefore, PET is a suitable measure of how closely a collision has been avoided. Because the post-encroachment time can only be used in cases in which one vehicle crosses the path of another, intersections provide a perfect application of this TCT. The value of PET depends on the acceleration behavior of the driver. To exclude these different driver behaviors, Allen introduced the **Initially Attempted Post Encroachment Time (IAPE)**. This measure is very similar to PET, however, in addition the expected time for the conflicted vehicle to reach the conflict point is added considering the speed achieved after the initial declaration rate was applied, as described by line (3) in Figure 6.1.

GETTMAN ET AL. [2003] include the **Maximum Speed (MaxS)** of both vehicles to decribe the serverity of the situation. MaxS is the maximum speed of both vehicles between the times T1 and T6. A higher MaxS indicates higher severity of the possible resulting collision. Furthermore, they use the **Maximum Relative Speed (DeltaS)** of the two vehicles involved in the conflict event as a measure of serverity. Higher DeltaS indicates higher severity of the resulting collision. DeltaS is initially defined (from the beginning to the end of the conflict event) as the difference between the velocity of the two conflicting vehicles for each time slice. The maximum of those DeltaS values for each time slice is taken as the DeltaS value.

HUPFER [1997] develops the **Deceleration to Safety Time (DST),** which is defined as the required deceleration of a vehicle in order to achieve a PET value of zero. In other words, the lowest deceleration required to avoid a collision with a conflicting vehicle or pedestrian. This measure is only applicable if a collision between a vehicle and another turning vehicle or crossing pedestrian is imminent.

The TCT measures presented so far are indictors for the identification of a conflict during the encounter of two road users, i.e. they deal with a single event. The TCT can also be applied to evaluate general road traffic safety. This should also be mentioned introducing the traffic conflict technique. MINDERHOUD ET AL. [2001] present two TTC-based measures, the **Time Exposed Time to Collision (TET)** and the **Time Integrated Time to Collision (TIT)** to analysis road traffic safety. TET measures the amount of time that a following vehicle spends below the threshold of a safe Time to Collision. According to MINDERHOUD, one disadvantage of the TET indicator is the fact that the TTC-value does not affect the TET indicator value if it is lower than the threshold. Therefore, he developed the Time Integrated Time to Collision indicator, which is the integral of the Time to Collision profile of drivers. This way the TIT also considers how far below the TCT threshold the TCT of a driver was. For further information on TCT for road safety evaluation, the work of HOFFMANN [2013] is suggested to consider.

6.2 Appropriate TCT Indicator for the Threat Assessment

Up to this point, the IRIS-System has estimated the possible maneuvers and predicted the vehicles and bicycles trajectories. The next step is to analyze the situation and determine whether there is the risk of a traffic conflict or not. Having introduced relevant TCT indicators suitable for intersection scenarios, it is important to decide which measures are applicable and meaningful for the threat assessment of the IRIS-System. The objective is to determine safety critical situations at the intersection as early and as accurately as possible to be able to trigger the message generation to avoid or at least to mitigate collisions by transmitting a warning to the driver.

ALLEN ET AL. [1978] propose the following ranging of the TCT indicators, Gap Time (GT), Post Encroachment Time (PET), Initial Deceleration Rate (IDR), Encroachment Time (ET), Initially Attempted Post Encroachment Time (IAPE) and finally the Proportion of Stopping Distance. It is important, however, to keep in mind that ALLEN observes real traffic first and computes the measures afterwards. In the case of the IRIS-system, the trajectories are predicted and therefore do only represent the real situation as is will occur up to a certain grade. For that reason, the ET and PET cannot be computed, as the knowledge of the real trajectories is obligatory. For the PET, this is line (2) in Figure 6.1. This cannot be computed either, as the point in time when the driver changes his speed again would be based on a prediction, too. The Initial DR is also a measure which is available after the driver recognized the encroachment. The possible change in the speed of the predicted trajectories is not suitable as a value for the Initial DR as it is an estimation of the driver’s real behavior.

The only two measures left are the Gap Time (GT) and the Proportion of Stopping Distance (PSD). Both values could be computed after the driver becomes aware of the encroachment of another vehicle or expressed in the systematic of the IRIS-System after the driver is within the awareness distance of a resistance point. However, GT and PSD have not been chosen for evaluation criteria. This is because it is not easy to define suitable thresholds when the situation becomes unsafe or critical for the driver. Intensive research would be necessary to figure out which Gap Times feel unsafe to a driver; and every driver has his/her own perception. For computing the PSD additional transformations would be required to establish a relation of the acceleration and the PSD.

As a result, another TCT indicator to be computed had to be found - the **Average Required Deceleration (ARD).** The ARD is the acceleration or declaration the vehicle needs from the first point of the trajectory to get in line with the required speed of the resistance point. In case the required speed of the resistance point is zero the ARD is like Hupfer’s Deceleration to Safety Time (DST) indicator [Hupfer, 1997]. The advantage of the ARD is that thresholds are quite easy to determinate. As already reported in paragraph 5.4 the average deceleration value for vehicle going at 50 km/h is about -5.5 m/s^2 and the maximum is about -8 m/s^2.

Based on this knowledge, appropriate thresholds for terminating a threat are defined initially. There is one threshold for safety warning messages at -3 m/s^2 and a lower threshold for really critical situations (less than -6 m/s^2). These initial thresholds need to be tuned during the testing phase of the IRIS-System, which is presented in paragraph 7.1.4.

To compute the ARD the core algorithm of the threat assessment (TA) goes through the set of reference tacks $\mathcal{K}$ including a loop through the subset of vehicles $\mathcal{I}_k$ assigned to that reference track. For each vehicle, the next valid resistance point is chosen, the type of the RP and herewith the situation which is to be assessed is determined. The TA differentiates four situations:

1) next RP referring to a vehicle right ahead[2]
2) next RP referring to a pedestrian crossing
3) next RP referring to a stop line
4) next RP referring to the intersection with a RT

To explain the concept, the scenario of two conflicting reference tracks is described in more detail. The result of the IME is the normalized probability p_{ik}^{norm} of the vehicle on the reference track. If this probability exceeds a certain threshold the assessment continues, otherwise it terminates. Furthermore, the IMA provides the prediction of the trajectories for each vehicle considering the resistance points. The prediction comprises eleven points of the vehicle's trajectory, while the first point at $t = 0$ represents the beginning of the trajectory. Additionally, the prediction comes along with the information on the vehicle's speed and acceleration. Figure 6.2 illustrates the predicted trajectory points and a RP referring to the intersection of two reference tracks.

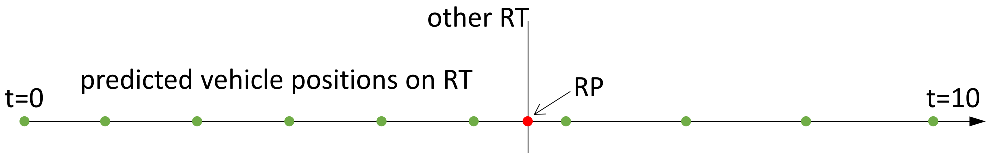


Figure 6.2 Illustration of predicted trajectory points and resistance point

The next step is to determine the following: the point of the prediction having the smallest distance to the RP before the vehicle passes the RP, the smallest distance going with that prediction point, the point in time when the vehicle will reach the RP, as well as the speed the vehicle has when reaching the RP. The predicted points for each vehicle need to be considered and the distance of the prediction point $t - 1$ to the resistance point is computed. If this distance is smaller than the half vehicle length +0.2 m or if the RP is in between the prediction point $t - 1$ and t, the closest distance is established. Figure 6.3 illustrates this approach. The line indicator expresses the part of the polyline segment a vehicle for instance has already covered in proportion to the complete length of the segment of the polyline combined with the cosine of the angle as already described at page 54.

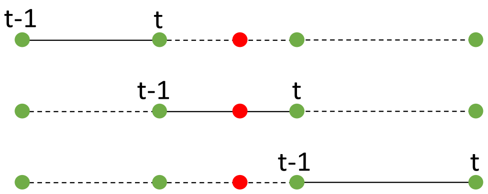


Figure 6.3 Illustration of prediction points before and behind a resistance point

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[2] This situation can theoretically be assessed, but is not the main purpose of the IRIS-System. Therefore, this situation is not elaborated further.

The **Average Required Deceleration (ARD)** to get in line with the required speed is computed by the quotient of the difference of the required speed of the resistance point and the speed of the vehicle at the beginning of the trajectory and the time the vehicle needs to reach the resistance point based on the predicted trajectory, which is named **estimated Time to Resistance Point (TTR)**:

$$ARD_{i,k}^{r} = \frac{v_{ik}^{req,r} - v_{ik,t=0}}{TTR_{ik}^{r}} \tag{6.1}$$

The estimated TTR is the difference of the point in time tp_{ik}^{r} when the vehicle reaches the RP and the point in time when the trajectory starts tp_{ik}^{0}:

$$TTR_{ik}^{r} = tp_{ik}^{r} - tp_{ik}^{0} \tag{6.2}$$

with

$$tp_{ik}^{r} = tp_{i.k,t-1} + \Delta t \cdot \lambda \tag{6.3}$$

with the line indicator λ as defined in equation (4.3) and Δt the length of one prediction time step. A safety warning will be generated and transmitted to the vehicle, if $ARD_{i,k}^{r} \epsilon \left[a_{safety}; a_{critical}\right[$ and if $ARD_{i,k}^{r} \geq a_{critical}$ a critical warning will be issued.

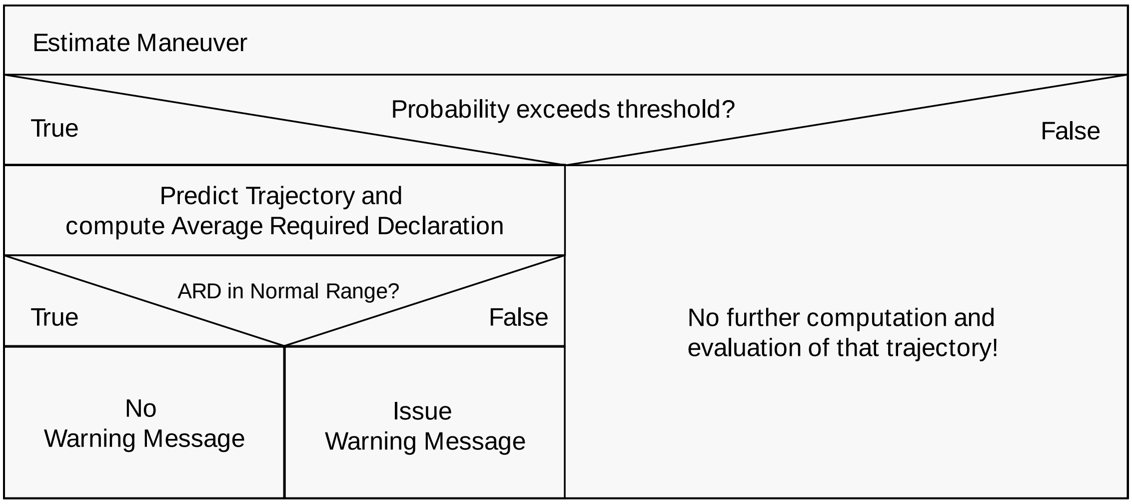


Figure 6.4 IRIS-System – from maneuver estimation to warning message

Figure 6.4 summarizes the complete process: first the maneuvers are estimated. In case the probability for a certain maneuver exceeds a predefined threshold (default value is 0.15) the IRIS-System predicts the trajectory and computes the Average Required Deceleration. The ARD is checked against the deceleration thresholds and if required a warning message is issued.

6.3 The Warning Message and the Drivers' Reaction

Once the IRIS-System has concluded that the driver needs to be warned a warning message is issued. This message is received by the transmitter onboard the vehicle and forwarded to the interior vehicle system for activating the human machine interface. Here the message is interpreted and the according icon is displayed to the driver on the dashboard of the vehicle. Figure 6.5 depicts the visual warnings to be displayed onboard of the vehicle, the left icon is used in case of an unsafe right turn because of a cyclist or a pedestrian, the right one is shown to the driver in case of the danger of violating the red light. The more critical the situation is, the larger the red triangle.

IRIS icon – unsafe right turn

IRIS icon – red light violation

Figure 6.5 Two examples for the IRIS visual warning icon

FEENSTRA did a survey on the difference of the acceptance of visual, acoustical and tactile way the IRIS warning is presented [SCHENDZIELORZ ET AL., 2010]. The visual information appeared on an onboard display (8-inch screen) close to the steering wheel. Two standard car speakers were used to provide acoustic information from the left or right direction. Finally, the driver seat was equipped with tactors to provide directional tactile information via the seat. The experts evaluated the HMI applied in TNO's instrumented vehicle INCA (Instrumented Car) a Volkswagen Passat. The acceptance in terms of perceived usefulness and perceived satisfaction was rated positive by the experts. The visual and acoustic warnings were rated as easy to understand. In addition, the tactile warnings were found to be better understandable compared to the visual/acoustic warnings.

To visualize the impact of the IRIS-System about two conflicting vehicles the time-distance diagram is used again. The situation is the same as before shown in Figure 6.1; one vehicle is going through the intersection while another one is crossing. In the case the driver is paying attention he perceives the crossing vehicle at time point T1 and starts braking at time point T2. As soon the driver perceives the situation as safe again he accelerates and continues his way. A human being having enough time to draw a necessary decision based on the surrounding traffic situation does a better job than a technical system. This is because a real driver perceives the traffic satiation in better overall view. Nevertheless, a real driver does not have the same preciseness as a technical system and drivers have different experiences and physical conditions that will influence their decisions [ABENDROTH ET AL. 2012]. Furthermore, Abendroth reports referring to Green (2000) that the driver reaction times are about 0.7 sec for anticipated situations and about 1.25 sec for unexpected situations up to 1.5 sec for astonishing situations. The more critical the driver perceives the situation the faster his reaction. However, the driver's reaction depends on a variety of aspects as there is e.g. the driving situation, his attention, the mental and emotional workload. But, does the driver not paying any attention in your theoretical example, because he is obstructed by a ringing smartphone or something else, he might continue along the dotted line (1) and passes the crossing vehicle with a certain gap time, as Figure 6.6 visualizes, or will collide (GT=0).

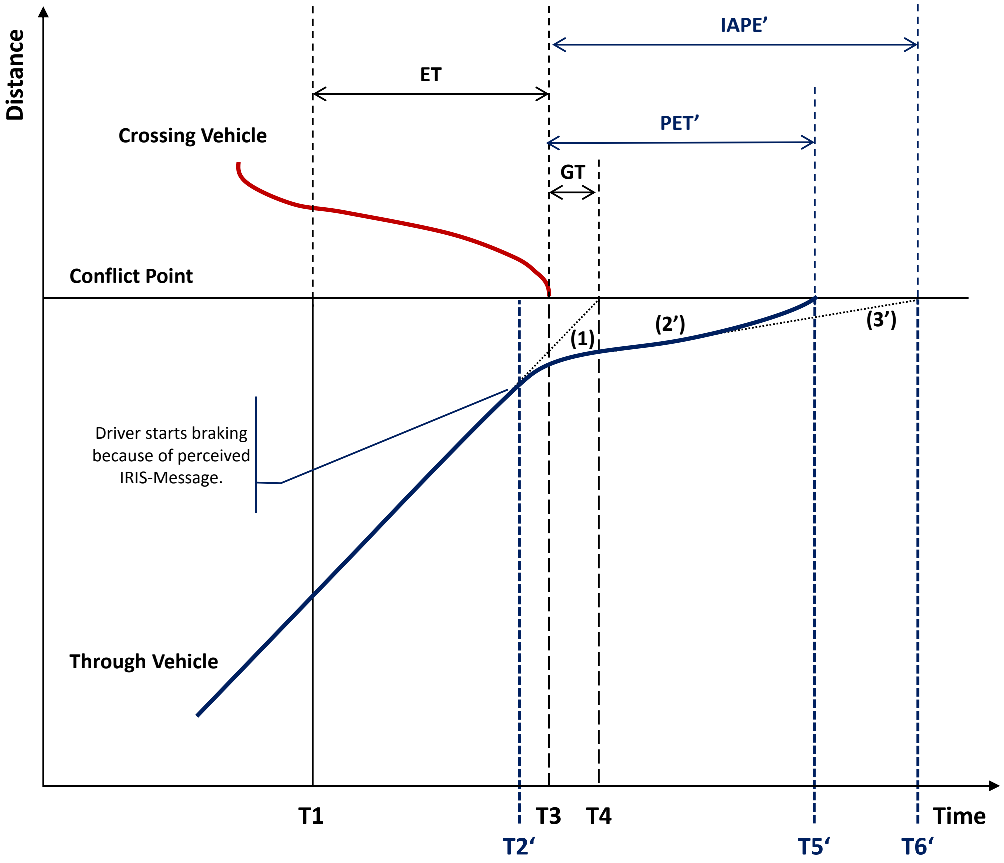


Figure 6.6 TCT measures on conflict point time-distance diagram with imminent conflict and IRIS-System interfering

The task of the IRIS-System is to avoid this probable collision. Figure 6.6 depicts the possibly dangerous situation including the intervention of IRIS. The driver does not get aware of the encroachment of the crossing vehicle, which starts at T1. The IRIS-System is observing and interpreting the situation and transmitting a warning message to the driver. As soon the driver perceives the IRIS-Warning on his dashboard in his vehicle he is assumed to brake immediately. This happens at time point T2'. To avoid the collision the driver needs to brake harder than he would do in the normal case and therefore the Initial Deceleration Rate (IDR) is higher than before; the gradient of the blue line (Figure 6.6) changes later to a smaller value than the gradient of the red line (Figure 6.1). The Encroachment Time (ET) and the Gap Time (GT) perceived at T1 do not change as they are not influenced by the driver's reaction.

However, the Post Encroachment Time (PET) and Initially Attempted Post Encroachment Time (IAPE) might change, as the driver brakes very hard in this example to an almost complete stop and then he continues and reaches the conflict point at a far lower speed compared to the dotted line (1).

One should note, that the point T2’ needs to be in a certain range. That means the driver should receive the warning as late as possible in order not to annoy the driver but early enough so the driver is able to stop the car in time. KOSCH [2006] reports on this warning dilemma and also on the different approach strategies of drivers while approaching a green traffic light. To elaborate a proper warning strategy driver behavior studies and research are required to tune the IRIS-System. However, the work on human machine interface and driver behavior is beyond the scope of proofing the systems concept and will not be investigated in more detail.

This fictive example explains the assumed impact of the IRIS-System. Based on the theory of the IRIS-System illustrated in the chapters before, the following paragraph is about proofing the concept of the IRIS-System and finding the most suitable parameters. Therefore, the testing is split into tests in the simulation laboratory using artificial data and tests at a real intersection.

7 Proof of Concept of the System

The proof of the concept is done in two parts; the first part is the virtual testing of the system and the main algorithms. Here the question shall be verified, whether it is possible to design a system, which is able to monitor and asses the driving maneuvers at an urban intersection. The second part reports on the tests of the IRIS-System at a real intersection in the City of Dortmund and verifies the hypothesis, whether it is possible to proof the system design at a real urban intersection. The tests at the real test site aimed to proof the capability of the system to cope with the conditions a real situation requires, such as communication range and time delays in the whole processing chain. In addition, the tests examine the correctness and timeliness of the received message in the vehicle. Before installing IRIS and its necessary components at the real intersection, virtual testing was used on the one hand, for adjusting the IRIS-System and testing the integration with the other parts of the system and on the other hand, for testing the maneuver estimation, prediction algorithms and the threat assessment.

IRIS and is components are not tested against any other system providing the same capabilities as IRIS does. There are two reasons for that: Firstly, at the time of designing and implementing IRIS, there was not similar approach of having a collision avoidance system predicting trajectories available on the market. Secondly, testing only some parts of IRIS against other approaches e.g. the maneuver estimation was not promising as these other approaches are vehicle based and having different and more input data to run the system as IRIS has. Therefore, the results of the test below are not interpreted against results from similar systems.

7.1 Testing the Algorithms in the Laboratory

7.1.1 Virtual Test Environment and Test Scenarios

Before installing IRIS at the real intersection, the technical functionality such as the interfaces to other components needed to be tested but also the performance of the main algorithms. For this purpose, artificial data is generated by using the microscopic traffic simulator VISSIM of the PTV Group [PTV VISSIM, 2013]. VISSIM allows modeling the road network topology, the individual movement of each vehicle and its interaction with the surrounding traffic, as well as the traffic light control. By utilizing the simulator's capability of logging the computed vehicle data such as position and speed for each time step and the traffic light control, it is possible to generate a set of data representing the input, as it will be at the real intersection. Therefore, the logged VISSIM files are manipulated in a way that this data represents the VANET messages from the vehicle and the messages from the traffic light control. This artificial data is fed into the real system, as it is implemented on the intersection in Dortmund.

General Settings and Preparations

For the virtual tests, the real intersection in the City of Dortmund was rebuilt in the microscopic traffic simulator. Figure 7.1 shows the real intersection of Hamburger Straße and Gerichtsstraße from the viewpoint along Hamburger Straße to the East. Hamburger Straße is a main road with two lanes in each direction and an additional separate left turning lane. The smaller side road, Gerichtsstraße, has one lane in each direction and there are no separate turning lanes. The speed limit is 50 km/h. Figure 7.2 presents a blue print of the intersection including the permanent installed roadside equipment, such as traffic lights and loop detectors.

Figure 7.1 Intersection Hamburger Straße/ Gerichtsstraße in Dortmund

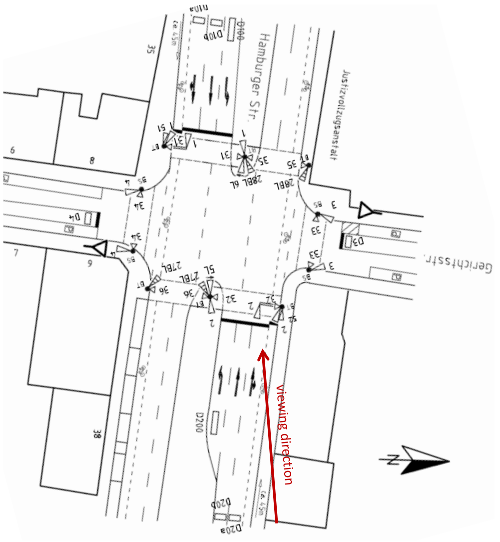
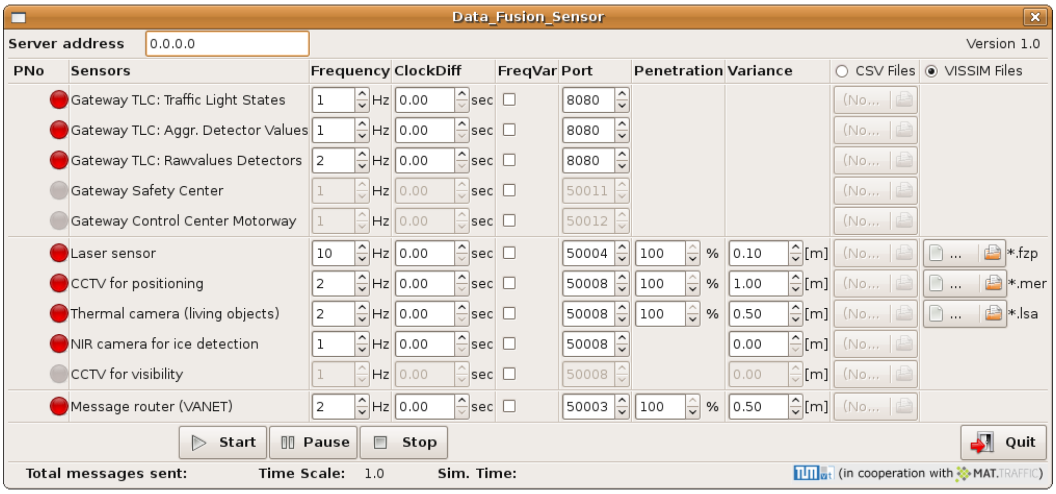


Figure 7.2 Blue print of the intersection

A special built module by MAT.TRAFFIC emulates the data on the vehicles' position and speed provided by the VANET based on the VISSIM log file. This data is fed into the *Data Receiver* (DR) of the IRIS-System using the same data protocol as for the real sensors and data transmission from the vehicles. Furthermore, the data received from the traffic light controller can be emulated. This also enables the developers to test the interfaces to the different data sources. This procedure was necessary before integrating the different components into the real system at the intersection.



Server address 0.0.0.0

Version 1.0

○ CSV Files ● VISSIM Files

PNo	Sensors	Frequency	ClockDiff	FreqVar	Port	Penetration	Variance		
●	Gateway TLC: Traffic Light States	1 Hz	0.00 sec	☐	8080			(No...	
●	Gateway TLC: Aggr. Detector Values	1 Hz	0.00 sec	☐	8080			(No...	
●	Gateway TLC: Rawvalues Detectors	2 Hz	0.00 sec	☐	8080			(No...	
○	Gateway Safety Center	1 Hz	0.00 sec	☐	50011			(No...	
○	Gateway Control Center Motorway	1 Hz	0.00 sec	☐	50012			(No...	
●	Laser sensor	10 Hz	0.00 sec	☐	50004	100 %	0.10 [m]	(No...	... *.fzp
●	CCTV for positioning	2 Hz	0.00 sec	☐	50008	100 %	1.00 [m]	(No...	... *.mer
●	Thermal camera (living objects)	2 Hz	0.00 sec	☐	50008	100 %	0.50 [m]	(No...	... *.lsa
●	NIR camera for ice detection	1 Hz	0.00 sec	☐	50008		0.00 [m]	(No...	
○	CCTV for visibility	1 Hz	0.00 sec	☐	50008		0.00 [m]	(No...	
●	Message router (VANET)	2 Hz	0.00 sec	☐	50003	100 %	0.50 [m]	(No...	

Total messages sent: Time Scale: 1.0 Sim. Time:

Figure 7.3 User interface of the data emulator for the virtual testing

However, for testing of the IRIS algorithms by using artificial data it is more important that the emulator is able to alter the input data. Changes in the transmission frequency, the difference in time of the data source and data receiver, the penetration rate of the equipped vehicles, which can be understood also as the detection rate for the sensors as well as the variances in meter of the emulated data, are possible, as Figure 7.3 shows. In addition to the emulator, a viewer was built by MAT.TRAFFIC displaying the intersection, as it is stored in the LDM, the trajectories and their prediction, as well the display of the warning messages. The viewer was important for checking the results of IRIS on a rough level and identifying elementary errors of the software, such as issuing the wrong warning message. Figure 7.4 visualizes the intersection as it is modeled in VISSIM and the scenario “red light violation”. Figure 7.5 shows the viewer displaying the same scenario with the according trajectories and issued warnings as they are reconstructed and generated by the IRIS-System for the situation modeled in the traffic simulator.

Figure 7.4 Intersection modelled in VISSIM

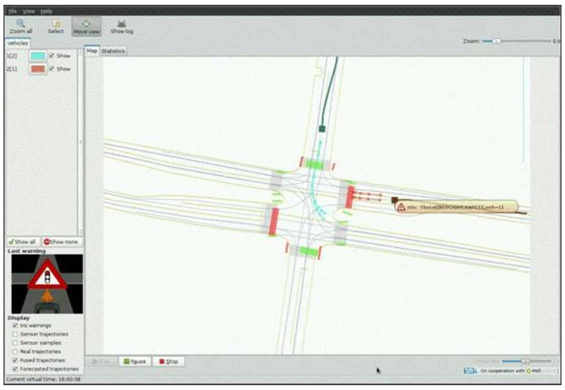


Figure 7.5 Viewer displaying trajectories and issued warnings

Transforming the VISSIM vehicle data into VANET messages

The most important elements of the VANET message are the time stamp, the position in WGS84 coordinates, the speed and the status of the indicator. As each vehicle, which can be viewed as a communication node, needs its own identification number, this node ID and the type of the communication node are included in the generated message. The VANET message is generated based on the vehicle record file of VISSIM, which contains vehicle number, vehicle type, simulation time step, coordinates in the VISSIM coordinate system, speed and the VISSIM link on which the vehicle is travelling. The vehicle number represents the node ID and the vehicle type is transformed into the node type of a communicating vehicle. The simulation time step is converted into UNIX time in seconds and milliseconds. For converting the VISSIM coordinates, an approximation is used. Firstly, one reference point in the microscopic simulation needs to be matched to a point at the real intersection. This could be for example the position of the beginning of the stop line. The coordinates of the point are stored in the static part of the Local Dynamic Map. Secondly, the meter coordinates of VISSIM need to be transferred into WGS84 degree coordinates. The equations (7.1) to (7.4) describe the transformation formula with $\overline{x_{VISSIM}}$ and $\overline{y_{VISSM}}$, the reference point in the VISSIM world, and $\bar{x}_{lat}$ and $\bar{y}_{long}$ the reference point at the real intersection in Dortmund in WGS84 degrees. The selected reference point has the coordinates of 7° 28’ 41.7046665’’ (East) longitudinal and 51° 30’ 52.5524298’’ (North) lateral, corresponding to 360.30 m VISSIM x and - 136,80 VISSIM y.

Transformation VISSIM [m] to WGS84 [°]:

$$x_{long} = (x_{VISSIM} - \bar{x}_{VISSIM}) \cdot \frac{360°}{2\pi \cdot r \cdot \cos(\varphi)} + \bar{x}_{long} \tag{7.1}$$

$$y_{lat} = (y_{VISSM} - \bar{y}_{VISSIM}) \cdot \frac{360°}{2\pi \cdot r} + \bar{y}_{lat} \tag{7.2}$$

Transformation WGS84 [°] to VISSIM [m]:

$$x_{VISSIM} = \left(x_{long} - \bar{x}_{long}\right) \cdot \frac{2\pi \cdot r \cdot \cos(\varphi)}{360°} + \bar{x}_{VISSIM} \tag{7.3}$$

$$y_{VISSM} = (y_{lat} - \bar{y}_{lat}) \cdot \frac{2\pi \cdot r}{360°} + \bar{y}_{VISSIM} \tag{7.4}$$

The approximation is the world seen as a normal sphere and so the transformation from meter to degree is done by assuming that the equatorial and the polar periphery of the sphere is set into the relationship of the 360° degree of a full circle. The radius r of the earth is assumed to be 6 378 137 m, which is the length of the half-axis of the WGS84 ellipsoid. As Figure 7.6 shows, the radius at latitude of about 51° and therefore the periphery is smaller than at the equator. Therefore, the radius needs to be multiplied with the cosine of the latitude, periphery of a circle.

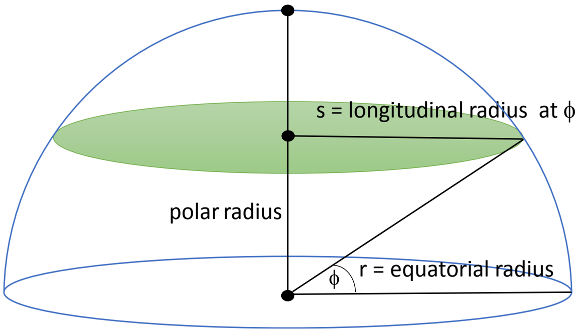


Figure 7.6 Approximation of radius at latitude of ϕ

Creating a network in the microscopic simulator VISSIM, a background image is needed on which the single links are constructed. Before that, the image needs to be scaled to the right size. For this purpose, a real reference length is needed. For the virtual intersection, the image of the graphic display taken from the geometric description of the real intersection in the LDM was taken. In this image the lanes, stop lines, pedestrian crossings and the reference tracks are visualized. Furthermore, two auxiliary lines in vertical and horizontal direction are drawn as reference lengths for the scaling of the image.

As the whole process of scaling and constructing the network is done manually, the result will never match reality perfectly. At a real length of 52 m in lateral direction the error in the VISSIM length is 1.17% and the error in the real coordinate converted to the VISSIM coordinates is 0.73%. In longitudinal direction at a reference length of 41 m, the error in the VISSIM length is 0.46% and the error in by converting the real coordinates is -1.31%. Although the VISSIM data does not represent the real world 100%, it will be taken as the reference value for the testing process later. The estimated values are compared against these reference values.

The four graphs in Figure 7.7 give an example of a vehicle crossing the intersection. The blue dotted line represents the VISSIM reference value. The orange line depicts the input value based on a standard deviation value of 0.0 m, the grey line is sigma 0.5 m, the yellow line is sigma 1.0 m and finally the green line with a sigma of 5.0 m. While the orange line matches the reference value well, the artificial generated positions of the vehicle deviated more the larger the standard deviation is.

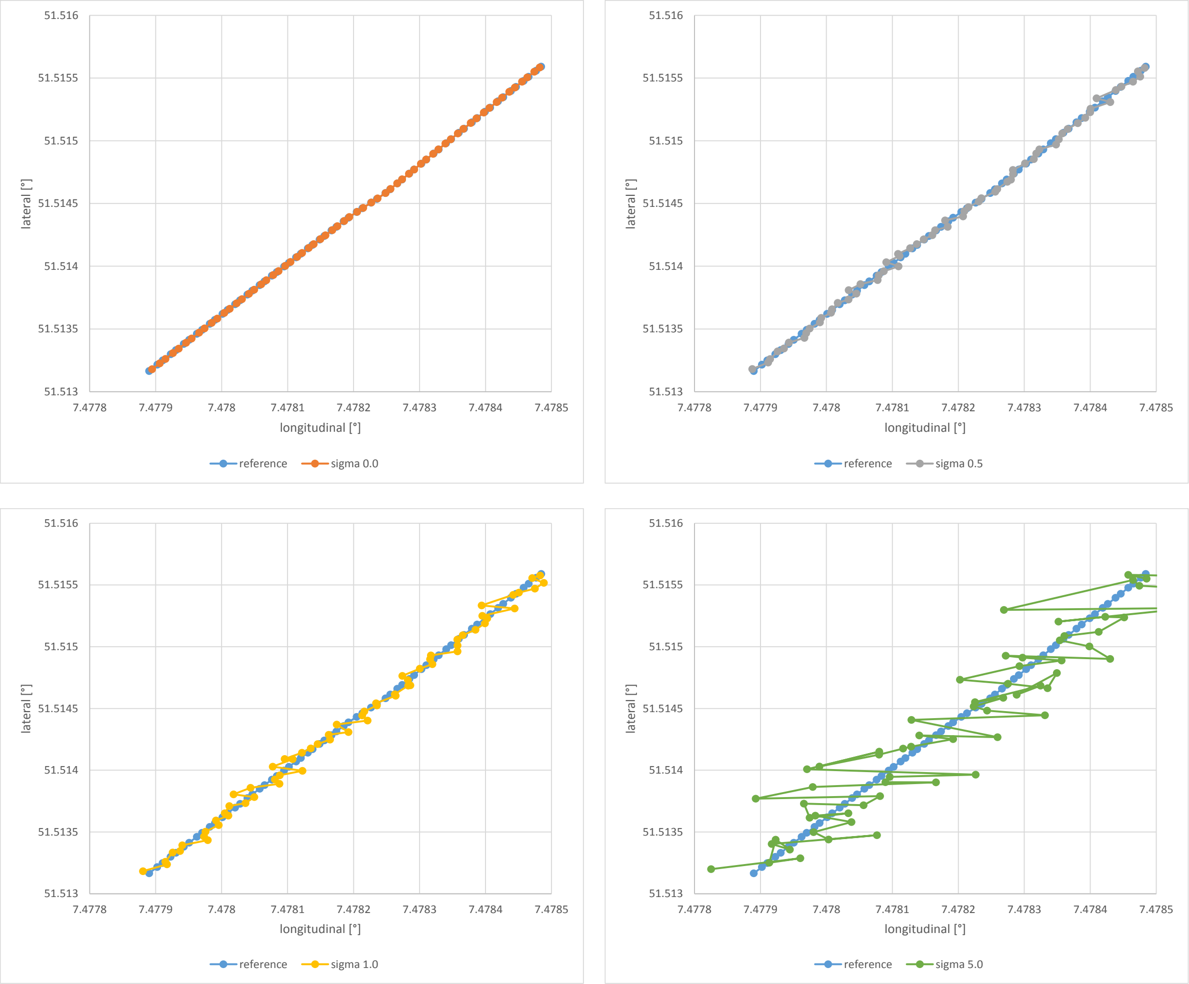


Figure 7.7 Example of input positioning values for the virtual testing

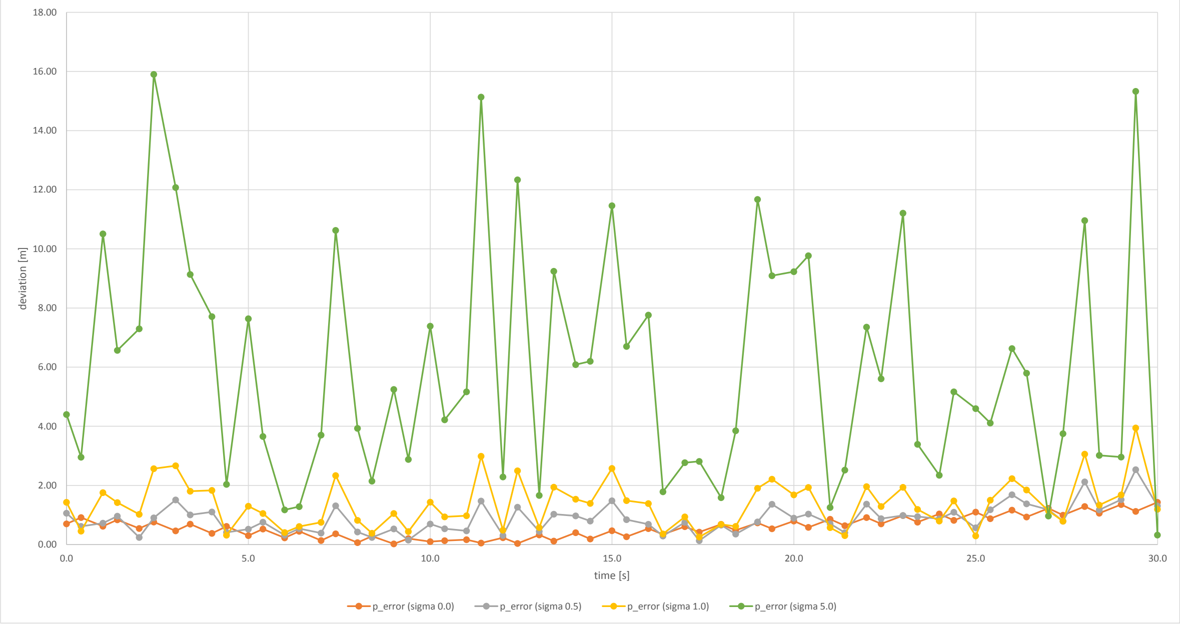


Figure 7.8 Deviation of the artificially generated positioning data

Figure 7.8 shows the deviation of the artificially generated positioning data in meter against the reference values. The green line indicates the deviation of the positions in the case of the standard deviation of 5.0 m. Here errors of more the 15 m can occur. The orange line (sigma 0.0) indicates that there is a basic error in the transformation of the VISSIM coordinates in the WGS84 coordinates. This error is nearly zero if the vehicle is close to the above-mentioned reference point. In this example, this is the case roughly after 10 s, when the vehicle hits the reference point. The further the vehicle is away from that point, the larger the basic error gets, which in this example equals about 1.5 m.

A proper conversion of the coordinates and date using the transformation of Helmert as described in [HOFMANN-WELLENHOF ET AL., 2008] would lead to truer results. It is not necessary to implement the proper conversation, since the VISSIM data gets altered anyway to serve as input data for the IRIS-System. Furthermore, the area of interest is focusing just on one single intersection, so the vehicles do not travel long distances, which means the change in the earth's ellipse does not have a huge effect on the conversion. A proper match with the real intersection with nearly no errors is rather impossible because the VISSIM network is constructed based on a manually scaled background picture. Finally, the indicator status is assigned to the VANET message. For the remaining data fields of the message set default values have been chosen to test the functionality of the whole date transmission.

The Test Scenarios

Based on the artificial data, the algorithms of the IRIS-System are tested. The results of the algorithms in the different process steps are compared to the artificial input data gathered from the microscopic traffic simulator. As the IRIS-System is a combination of the estimation of the maneuvers, the prediction of the trajectory and the threat assessment of the situation, the tests follow this sequence as well. Firstly, the estimation of maneuvers is tested based on data originating form single vehicles in different environment and without having any conflicts (see Table 7.1).

No.	Scenarios for Virtual Testing	Maneuver	Trajectory	Threat
1	no conflict – crossing – one lane	X	X	
2	no conflict – crossing – two lane	X		
3	no conflict – right turn	X		
4	no conflict – left turn	X	X	
5	no conflict – following		X	
6	conflict – red light – crossing – stopping		X	X
7	conflict – red light – crossing – violating		X	X
8	conflict – vehicle – left turn		X	X

Table 7.1 Overview of the scenarios for the virtual testing

These scenarios are the simple crossing and turning of the vehicles on a one and two-lane approach of the intersection. Secondly, the prediction of the trajectory is analyzed. Here also scenarios with conflicts are included. Finally, the threat assessment is investigated. In this context only scenarios with conflicts are meaningful. The conflict with a red traffic light, with an oncoming vehicle while turning left and a parallel riding bicycle while turning right are investigated. Table 7.1 gives an overview on the test scenarios. The details for each test are described right before reporting the results.

7.1.2 Testing the Estimation of Maneuvers

For the performance analysis of the estimation of the maneuvers, it is important to investigate whether the maneuver of a vehicle can be estimated correctly and which probability is assigned to the estimated maneuver. The trajectory of just one single vehicle will be analyzed in order to establish the behavior of the algorithm. As bicycles are treated in a similar way as vehicles, only with lower acceleration and deceleration capabilities, no special tests for bicycles are foreseen. Furthermore, the bicycles in the test scenarios are assumed just to ride along the bicycle path parallel to the main road. That makes maneuver estimation futile.

From the recorded VISSIM files, it is obvious which maneuver the vehicle executed and on which lane the vehicle was going. This is taken as the ground truth. The estimated trajectories are logged during the computation. Each trajectory and the current time step in which the estimation is done, the reference track to which the vehicle is assigned and the probability value for each estimation are available for this analysis.

The algorithm for estimating the maneuvers consist of different parts as described in Chapter 4. To analyze the influence of these components the algorithm will be altered slightly. Therefore, the components of the algorithm will be modified or even completely switched off or the accuracy of the input data will be changed to alter the effect of some parts of the algorithm. Firstly, the performance of the geometric matching is tested by disabling the influence of the driving direction and the turn indicator on estimation processes and feeding the algorithm with vehicle positions with different quality. The variance of the vehicle positions is changed, starting with standard deviations of 0 m, 0.5 m, 1.0 m and 5.0 m. Secondly, the input data is kept on a constant deviation value of 0.5 m, but the algorithm results are compared against each other. At first only geometric matching is used to estimate the maneuver, as a next step driving directions are included in the estimation, and finally the indicator with a low and finally with a high influence factor is considered as well. The factors for low influence are 1.0 for straight going vehicles and 2.0 for turning vehicle for the direction the turning signal is pointing. High influences have the values 2.0 and 4.0.

For testing the geometric matching capabilities of the algorithm, the data of a vehicle approaching from Gerichtsstraße and crossing the intersection on RT 6111 are analyzed first (see Figure 7.9). This street only has one lane per direction. Secondly, the data of a vehicle approaching from Hamburger Straße at RT 6106 is used for the estimation. This is an approach of the intersection with two lanes and a separated left truing lane. The data of a vehicle turning left on a separated lane modeled by the RT 6108 is the third input for the algorithm.

Approach Gerichtsstraße – One Lane – Vehicle Crossing

Figure 7.9 is depicting the bundle of reference tracks which need to be considered by the estimation algorithm for the case a vehicle is approaching from the north on Gerichtsstraße. This is a bundle of five RTs, because the in-turning vehicles can select one of two lanes for their maneuver. Figure 7.9 shows the ID of the RTs, too.

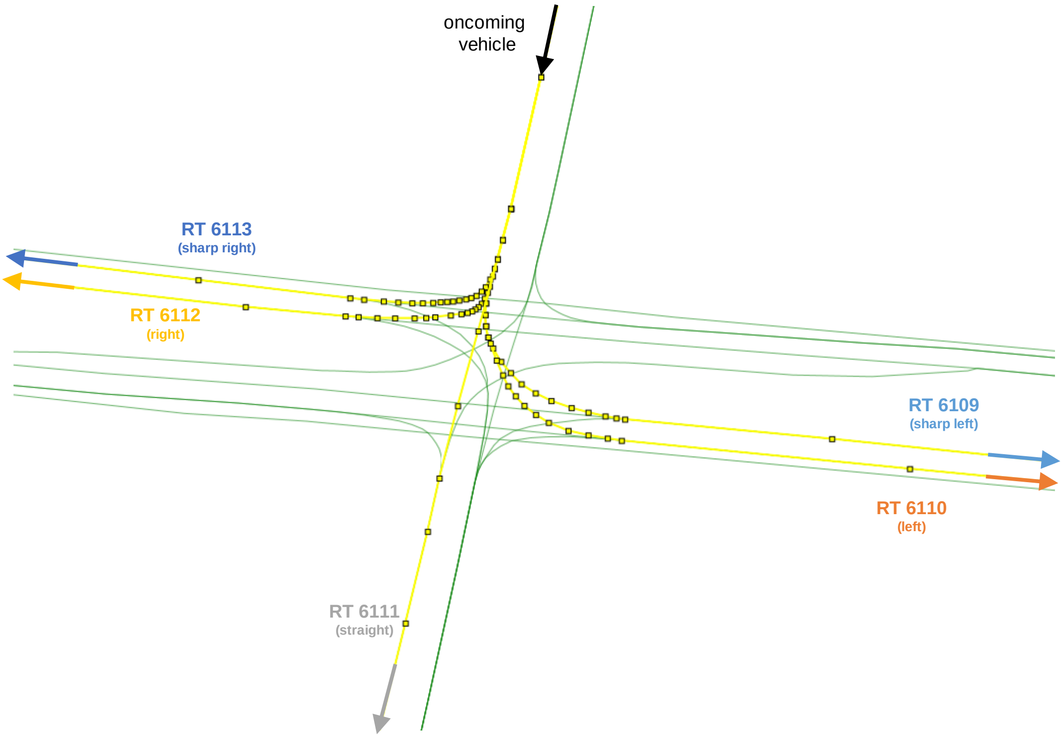


Figure 7.9 Possible maneuvers for vehicles approaching from Gerichtsstraße

The graphs in Figure 7.10 show the results of the estimation with a standard deviation of 0.0 m, 0.5 m, 1.0 m and 5.0 m. The estimated probability of a vehicle crossing the intersection is on the y-axis. The elapsed time from the first time the system detected the vehicle through reception of a VANET message of the vehicle is plotted on the x-axis in seconds. As there are more options for the vehicle to take, there is also more than one probability-reference track pair at each time step. In this example, the vehicle is assigned to five RTs, and each assignment has its own probability value. The included stop line is drawn on the point in time when the vehicle crosses the line. This is always at the same point, because the system gets aware of the vehicle at the same point in time regardless of the standard deviation of the vehicle's position.

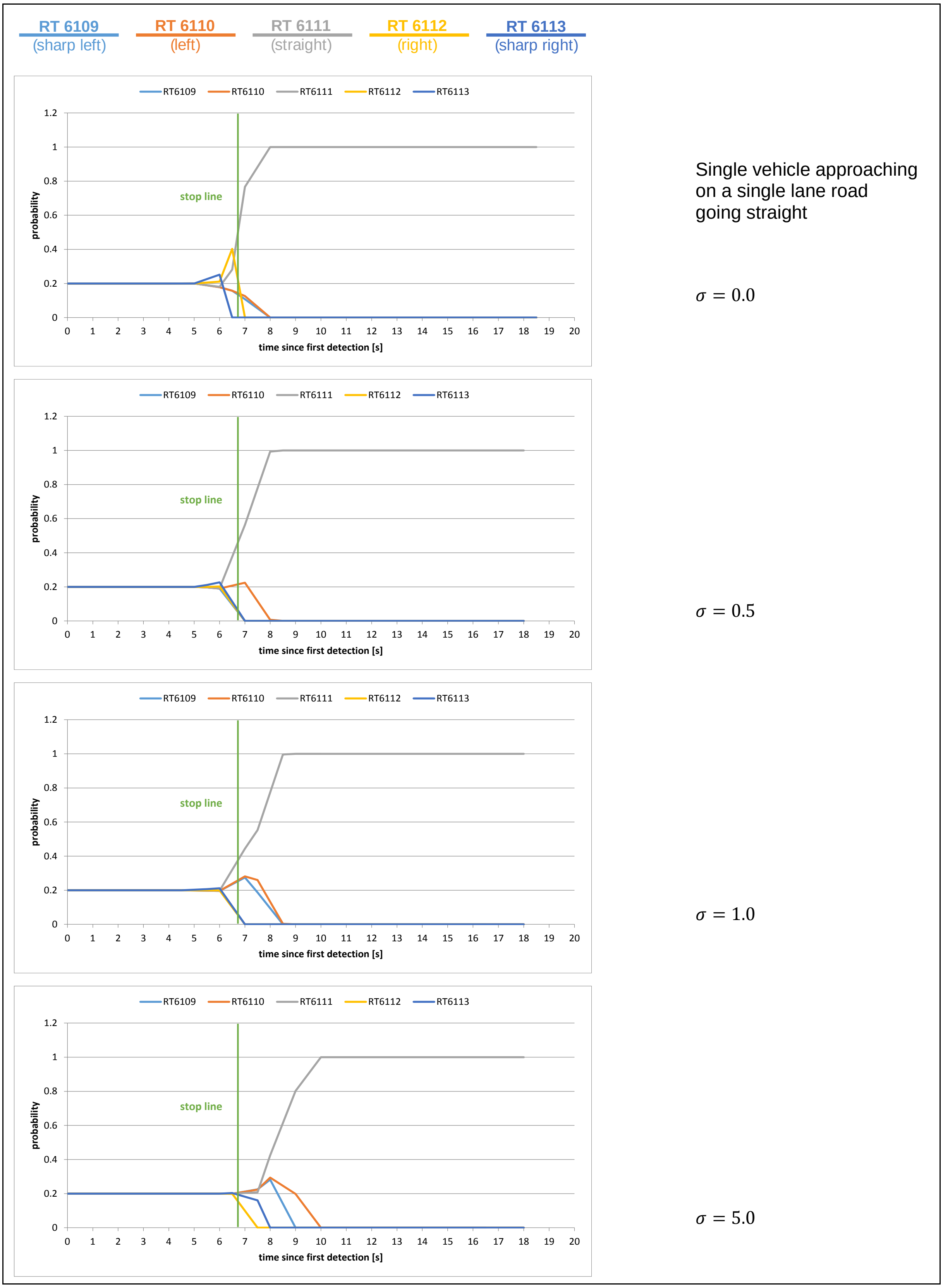


Figure 7.10 Probability distribution of a single vehicle crossing the Intersection approaching from Gerichtsstraße estimated only using geometric matching by different standard deviation of the vehicle's positioning values

Before the vehicle reaches the stop line, the probability for each assignment is 0.2. This is because only the position for estimating the maneuver and the RTs overlap in the approach of the intersection were considered. Therefore, no differentiation is possible and each assignment is equally probable. This changes as soon as the RTs do not overlap exactly anymore. This is right before the stop line, about 1.0 to 1.5 s before the vehicle reaches the stop line. The first graph in Figure 7.10 shows the results for highly accurate position values - the standard deviation equals zero. As RT 6113 (dark blue line), the track modeling the right turning maneuver onto the right lane of the main road, is the first track branching off, it is obvious that its probability is decreasing also at first.

The second track branching off is RT 6112 (yellow line). Its probability is evidence of that fact, too. The minor peaks in the probability of these RTs are due to the limited accuracy of constructing the RTs. As soon as the right turning tracks and the RTs modeling the left turn maneuver (RT 6109 and RT 6110) do not need to be considered anymore, the probability for the RT going straight (RT 6111 – grey line) increases. It reaches its maximum at that point the RT 6109 and RT 6110 are out of scope.

Reducing the accuracy of the positioning, the first finding is that the peaks in the probability of the RT 6113 and 6112 disappear before the stop line. This is since the positioning values are less accurate than the deviations of the overlapping RTs at the part of the intersection. However, the probability of the two left turning tracks shows a small peak, because the position is not accurate enough for identifying the track branching off immediately. These observations show how sensitive the geometric matching works and how important accurate reference tracks are. The larger the standard deviation gets, the larger the peak in the probability of the two left truing RTs will get and the later the system will be able to estimate the real movement of the vehicle. With a σ of 5.0 m the estimation of the correct movement is not able to estimate the correct maneuver before the stop line is reached, as the last graph of Figure 7.10 shows.

Approach Hamburger Straße – Two Lanes – Vehicle Crossing

The next test deals with the vehicle entering the intersection on a two-lane approach, while constantly going on the right lane. Figure 7.11 is showing the possible maneuvers, with similar reference tracks a vehicle approaching from the East on Hamburger Straße would have. Here the vehicle has four options for its maneuver.

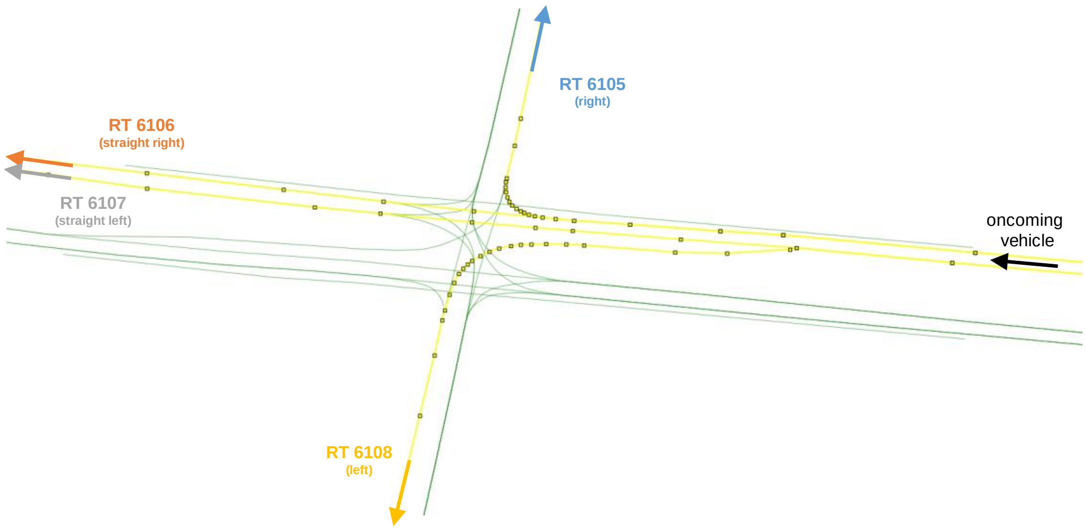


Figure 7.11 Possible maneuvers for vehicles approaching from the east at Hamburger Straße

The vehicle crosses the intersection on RT 6106 (orange line in graphs of Figure 7.12). Up to the stop line, RT 6106 overlaps with RT 6105 (blue line) and the RT 6107 (grey line) and the RT 6108 (yellow line) are located on the left lane. The first graph of Figure 7.12 shows that the algorithm fed with accurate position values is able to allocate the vehicle to the correct lane. As soon as the right turning RT 6105 branched off, the probability is also between 0.9 and 1.0. Before, the process evenly distributed the probability value between the right straight going lane and the right-turning lane, as there is not additional information included yet in the algorithm. After increasing the value of the standard deviation, the allocation to the correct lane is still possible at a level of σ of 0.5 m, but the orange and grey line are getting closer the larger σ gets. At a value of $\sigma = 5.0$, there is no more allocation to the right lane with a high probability value is possible. The values for RT 6106 and 6107 oscillate at about 0.5. This behavior of the algorithm is evident, as the width of the lane is set to 3.5 m, which is smaller than the standard deviation of 5.0 m. In addition, the algorithm takes longer to recognize the branching of the reference tracks compared to low standard deviation values. This is the similar behavior as in the test before.

As the test shows, the estimation of maneuvers based solely on geometric information provides good results for low standard deviation values. However, in the case of higher standard deviation poorer quality is achieved. Consequently, more pieces of information need to be included in the algorithm to gain better results. The following section will report on the influence of this added information.

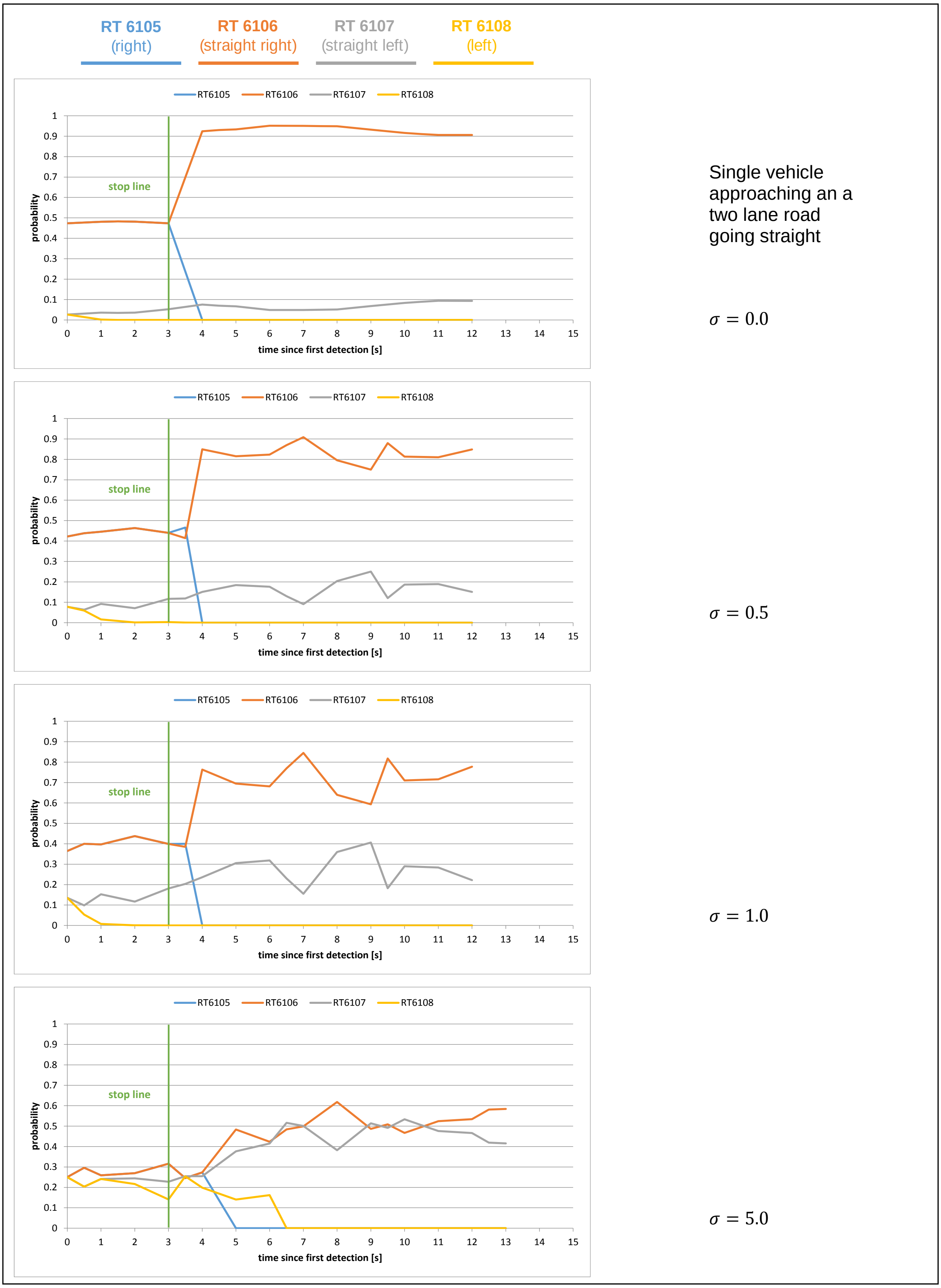


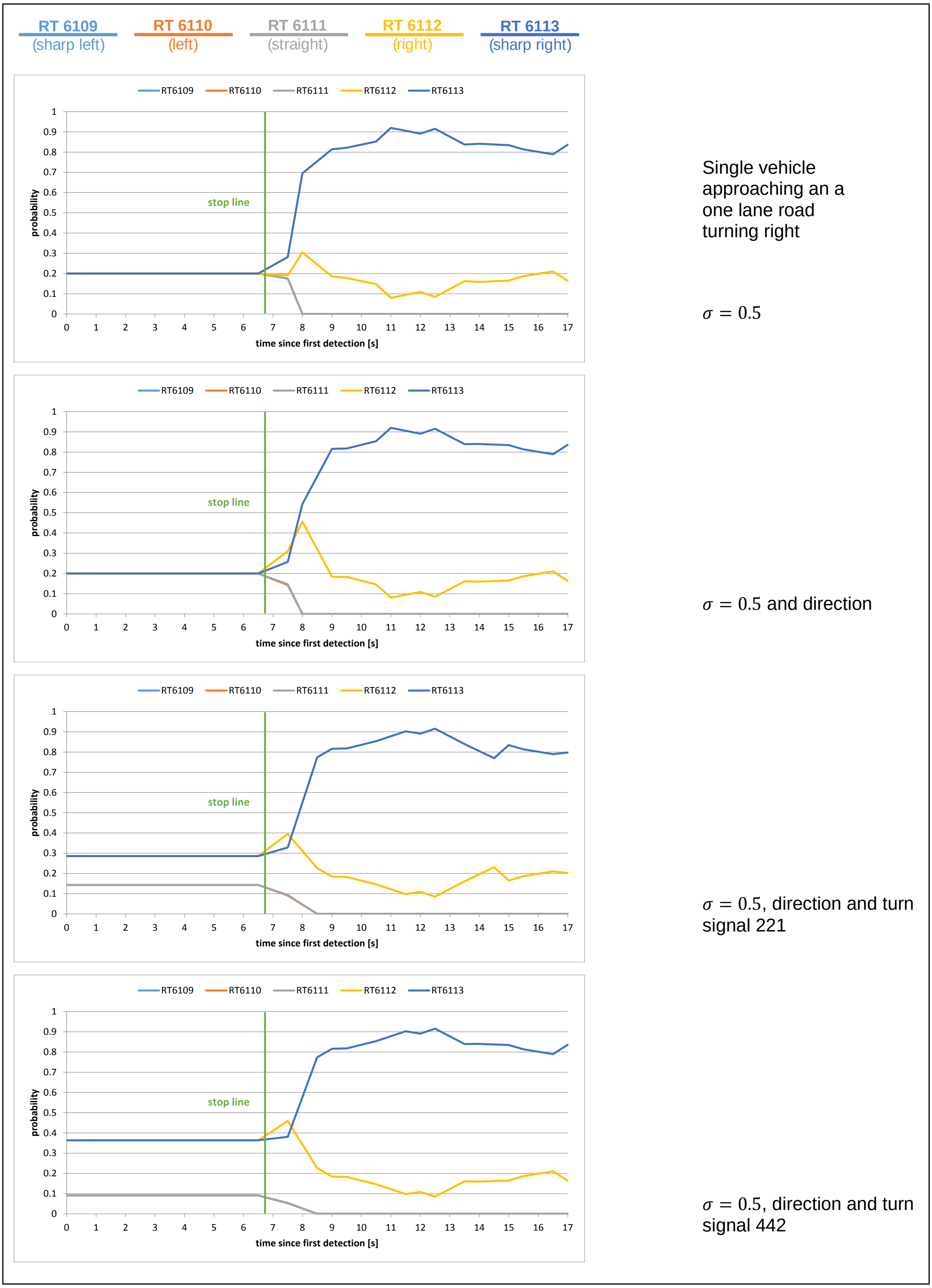
Figure 7.12 Probability distribution of a single vehicle crossing the intersection approaching from Hamburger Straße estimated only using geometric matching by different standard deviation of the vehicle’s positioning values

Approach Gerichtsstraße – One Lane – More Information Included

During the first tests, the estimation algorithm only runs in its basic version. Now the deviation angle from the driving direction of the vehicle and the direction of the reference track and the turn signal are included successively. The standard deviation of the position of the vehicle is set to a constant value of 0.5 m.

The graphs in Figure 7.13 show the probability of a single vehicle turning right at the intersection approaching from Gerichtsstraße. Figure 7.9 depicts the reference tracks on this approach of the intersection. The vehicle turns onto the right lane of the main road Hamburger Straße. As proven in the test before, the maneuver estimation is able to allocate the vehicle in case of two lanes leading in the same direction on the correct lane in a quite reasonable way. The drawing of the RT 6113 (blue line) and the RT 6112 (yellow line) demonstrated this again. As this right turn maneuver is a rather sharp bend, the deviation of the vehicles direction and the direction of the RT is just right after the stop line in a sharp way so that the influence is nearly negligible.

Before the stop line, no preferred maneuver is identified. The algorithm considering the turn signal can manage this. Including the turn signal the results of right turning tracks from the others are separated by increasing their probability, as the two last graphs of Figure 7.13 report. It is obvious that the impact of the turn signal increases when high factor values are used. The shape of the lines is identical compared to the results with or without the turn signal. This is because the computed probability values are modified when including the influence of the turning signal by adding certain factors. A similar behavior of the algorithm can be observed in the case of the vehicle crossing the intersection. In this case, only the high influence factor of the turn signal shows an effect. This is because a driver might forget to signal before turning. Figure 7.14 plots the results of the described test cases.



Single vehicle approaching an a one lane road turning right

$\sigma = 0.5$

$\sigma = 0.5$ and direction

$\sigma = 0.5$, direction and turn signal 221

$\sigma = 0.5$, direction and turn signal 442

Figure 7.13 Probability distribution of a single vehicle turning right at the intersection approaching from Gerichtsstraße estimated using geometric matching, direction and turn signal

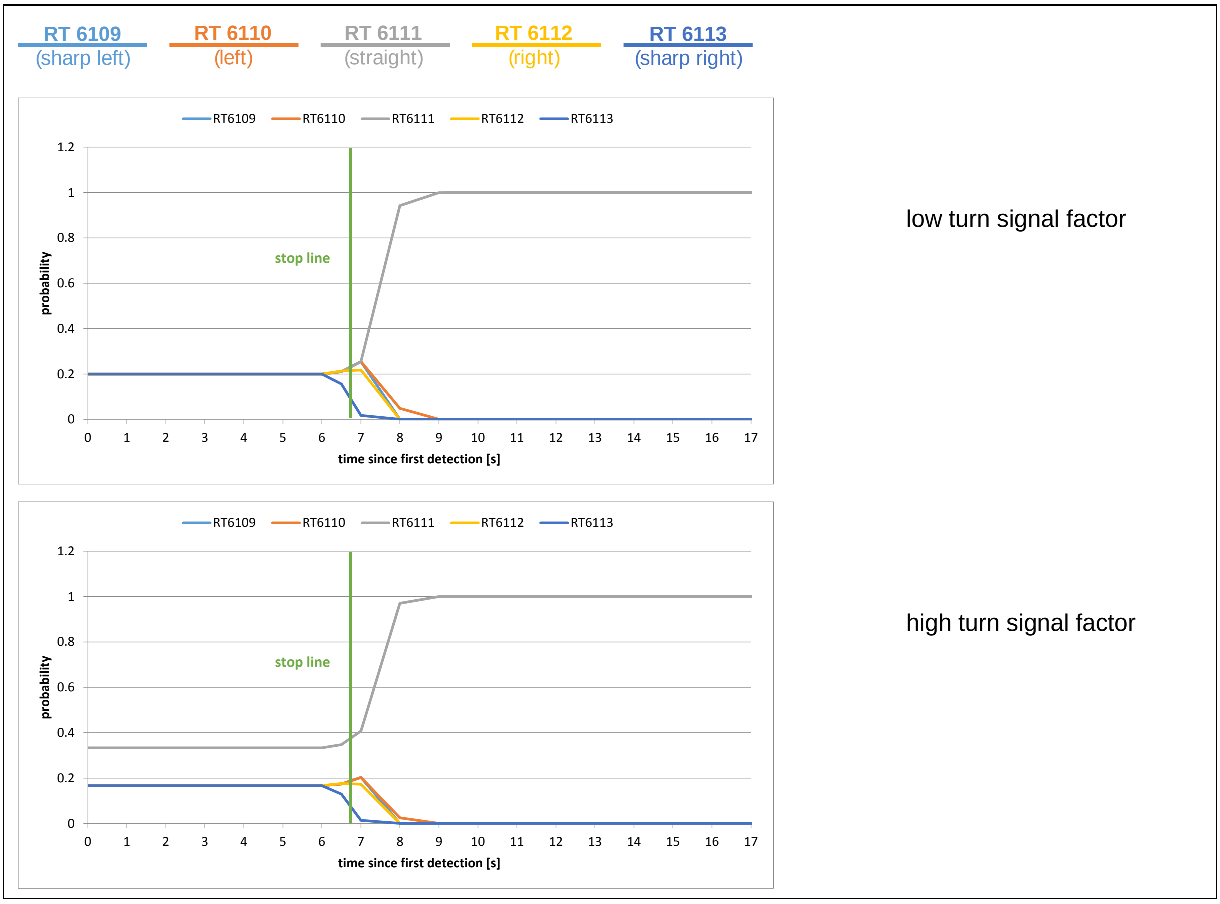
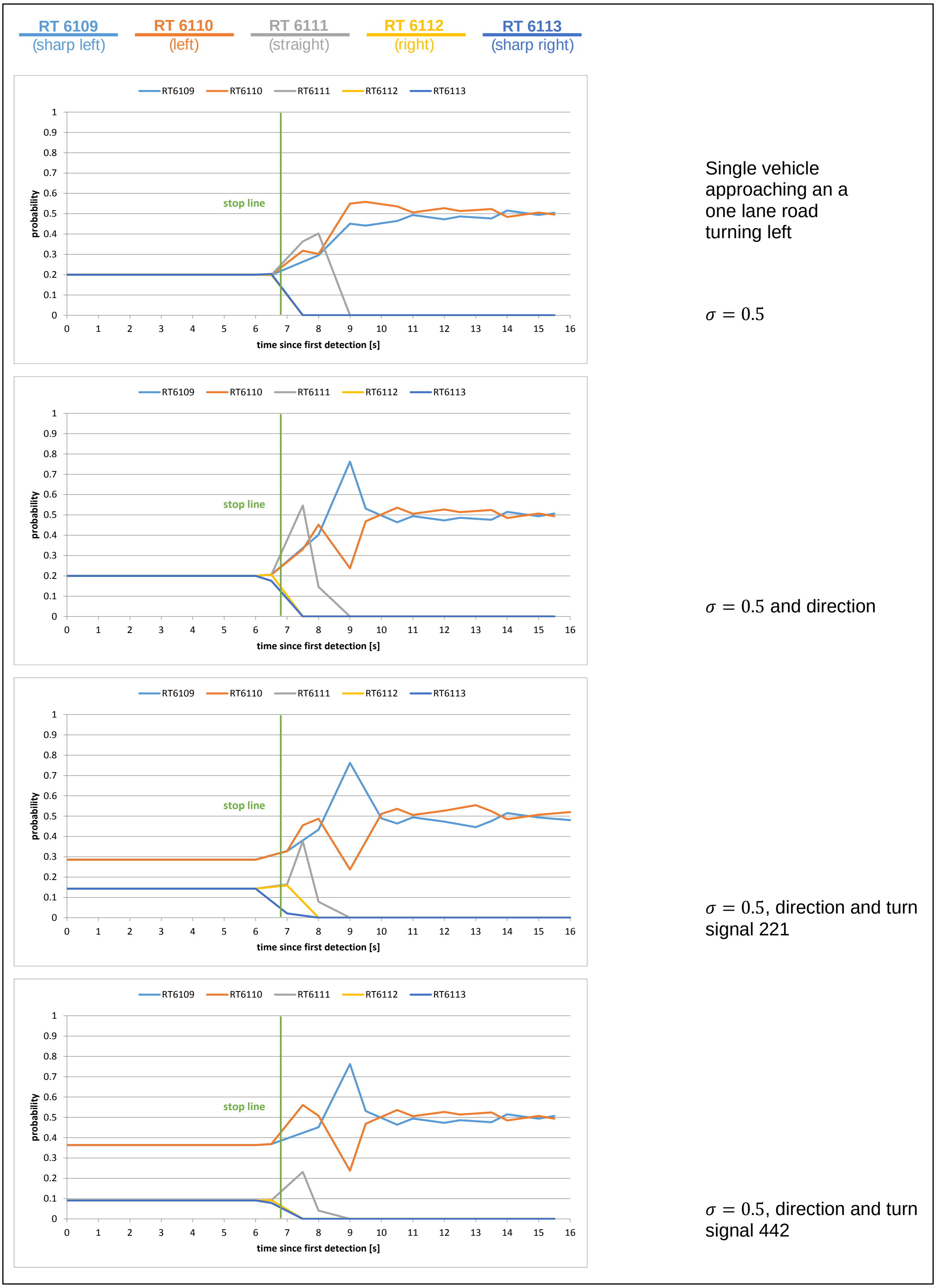


Figure 7.14 Probability distribution of a single vehicle crossing the intersection approaching from Gerichtsstraße estimated using a low (left) and a high (right) turn signal factor

The graphs in Figure 7.15 display the results for the left turning vehicle approaching from the Gerichtsstraße. Here a similar influence of the turn signal can be observed. The peaks in the probability lines are noticeable once the direction of the vehicle and the reference track is included; one in the probability line of RT 6111 (grey line) for going straight at time point 7.5 sec and another one in the line of the RT 6109 (light blue line) turning in at the left lane at time point 9 sec. The reason for this is that their directions are different for the area, in which the two left turning RTs separate. Whereas leading onto the two straight lanes of the main road, their direction is identical again, as before the branching off. Exactly this fact leads to a higher probability of the maneuver when the direction of the RT and the direction of the vehicle match better. The same argumentation holds for the RT going straight. As soon as the vehicle passes the point at which the two right turning RTs branch off, it leads to a higher value for the RT 6111 when the directions are included. This effect vanishes immediately as the direction of the RTs is identical again.

These observations offer a possibility for further improvement of the algorithm. The peak in the probability could be included in the estimation processes. So, the information of the direction is still included and not lost as soon the vehicle goes parallel to the reference track. However, this was not implemented and tested in the scope of that work.



Single vehicle approaching an a one lane road turning left

$\sigma = 0.5$

$\sigma = 0.5$ and direction

$\sigma = 0.5$, direction and turn signal 221

$\sigma = 0.5$, direction and turn signal 442

Figure 7.15 Probability distribution of a single vehicle turning left at the intersection approaching from Gerichtsstraße estimated using geometric matching, direction and turn signal

Conclusion

The test showed that the algorithm always assigned the correct maneuver to the vehicle in different scenarios. Geometric matching identified the lane on which the vehicle was driving on correctly, but only up to a standard deviation of 0.5 m. This underlines the importance of the prerequisite of a highly accurate positioning technique for the vehicles in safety applications. A powerful positioning unit is also mandatory for applications dealing with an approach advice for efficient crossing at the intersection, as it was investigated in the eCoMove project.

For the estimation of the maneuver of the vehicle before crossing the stop line or the branching of the reference tracks additional information is necessary. In the case of the IRIS-System, the turn signal of the vehicle was considered, which improves the results of the estimation. It needs to be kept in mind that the use of the turn signal still includes the human being in the loop of the estimation process. Therefore, as already assumed in section 4, more information is needed to be included to make the estimation more reliable and more sufficient in time. Additional pieces of information might be the speed of the vehicle, as a vehicle will approach a green light with a slower speed when it is about to turn left as if it was about to go straight. Another point for further improvement is the tendency of the algorithm to drop information about the deviation of driving direction and reference track and not using it for the further estimation.

7.1.3 Testing the Prediction of the Trajectories

The estimation of the vehicles' maneuver follows the process of the prediction of their movements in the next few seconds. The concept of the resistance point, as described in section 5.3 forms the basis for the prediction. The aim of the following tests is to proof this concept by appropriate error measures and comparison of the real against the predicted trajectory.

For this analysis, it is important to distinguish between two different points of view on the prediction; the lateral and the longitudinal point of view. The longitudinal point of view observes one single prediction including 10 predicted waypoints. The lateral point of view analyzes the results of the prediction at e.g. all second prediction steps with different starting points in times of the prediction. Figure 7.16 depicts this in a simplified way. The x-axis indicates the time and the y-axis the position. The blue lines represent the trajectories built from the predicted waypoints (red). The grey areas visualize the two different views for the analysis. For a better graphical representation, the picture is consciously distorted. The positions for the prediction are on a different scale as for the positions of the starting point of the prediction. If this was not the case, all the predicted trajectories would overlap with an offset in time to the starting point of the next prediction; 500 ms in this case.

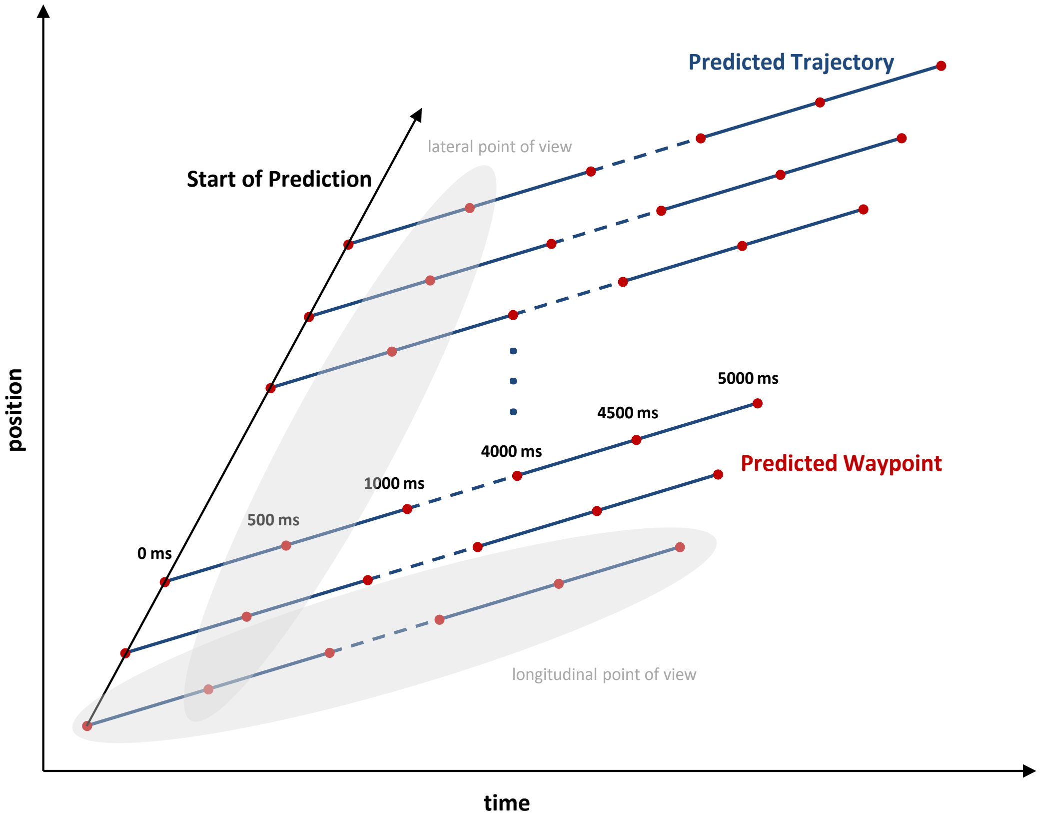


Figure 7.16 Distorted view on the prediction

The basic scenario for the analysis is a vehicle travelling from North to South and crossing the intersection on green light (see Figure 7.9 at page 97). The following parameters have been changed to analyze the sensitivity of the algorithm:

- the standard deviation of the vehicle's position and
- the length of a prediction time step.

The point of view for this first test is the lateral one. Assessing the quality of the prediction, it is necessary to describe the difference between the virtual input values x generated by VISSM, representing ground truth, and the result of the prediction y. For computing the error measures, the predicted values need to be aligned to the respective points in time of the VISSIM input values. The values, which are compared against each other, are the latitudinal and the longitudinal position, the absolute error in the position, the speed and the distance traveled at each prediction step. The following error measures allow a statement on the quality of the prediction, where N is the number of samples:

The **mean absolute error** (MAE) is an indicator for the bias of the prediction regardless of whether the deviation is positive or negative.

$$e_{MAE} = \frac{1}{N}\sum_{n=1}^{N} x_n - y_n \tag{7.5}$$

The **root mean squared error** (RMSE) is also insensitive against the positive or negative errors. The difference to the MAE is that larger errors are weighted more than in the MAE.

$$e_{RMSE} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(x_n - y_n)^2} \tag{7.6}$$

The **maximum absolute error** (MAXE) displays the value with the largest bias regardless its algebraic sign.

$$e_{MAXE} = \max_{N}(x_n - y_n) \tag{7.7}$$

The last indicator for the prediction quality is the **correlation index** (COR). The value of the COR lies between -1 and 1. Value 0 means that there is no correlation between the two compared sets of value. The closer the COR gets to -1 or 1, the larger the correlation will be. The value -1 means that there is a negative correlation and 1 indicates a positive correlation.

$$cor(x,y) = \frac{cov(x,y)}{\sigma_x \cdot \sigma_y} \tag{7.8}$$

where $cov(x_n, y_n)$ is the covariance of x and y and σ denotes the standard deviation.

For testing the RP-concept the longitudinal point of view was chosen. For these tests, the prediction time step and the standard deviation of the position were kept to the constant value of 0.5 s and 0.5 m, as it was done for testing the maneuver estimation, too.

The following scenarios for the virtual testing are dealt with:

- no conflict – crossing – one lane
- no conflict – left turn
- no conflict – following
- conflict – red light – crossing – stopping
- conflict – red light – crossing – violating
- conflict – vehicle – left turn

Lateral point of view: Approach Gerichtsstraße – One Lane – Vehicle Crossing

The test scenario comprises a vehicle traveling on a street with one lane and crossing the intersection while the traffic lights are green. As the lights are green and no other road users are in the system, there are no conflicts and so the RPs do not set strict boundaries to the prediction (see section 5.2). The vehicle is assigned to RT 6111, which is the one in middle of Figure 7.9 at page 97. During the time, the vehicle is in the area of interest, the prediction was executed about 30 times. That means 30 times, 10 waypoints were computed and recorded including the starting point of the prediction. The length of the prediction time step was set to 0.5 s. Therefore, the prediction horizon expands up to 5 s into the future. The next two sections report the results of the quality of the prediction from the lateral viewpoint.

Different Standard Deviation and Constant Length of Prediction Time Step

Table 7.2 presents the mean absolute error (MAE) of the crossing vehicle at different input quality of the vehicle's position, starting with a standard deviation of 0.0 m up to a deviation of 5.0 m. The error values in the first line at prediction step 0 are based on the generated VANET messages based on the VISSIM log files. Even the first value in the column with no standard deviation shows an error of 0.2135 m. This is due to the inaccuracies in the transformation of the positions into the different formats and the slight mismatching of the VISSIM intersection to the intersection represented in the Local Dynamic Map.

Prediction Step [ms]	**Absolute Position [meter] --- Mean Absolute Error**			
	sigma 0.0 m	**sigma 0.5 m**	**sigma 1.0 m**	**sigma 5.0 m**
0	0.2135	0.3494	0.5759	1.9655
500	1.0866	1.3166	3.3950	3.1532
1000	1.6987	2.1653	4.4663	3.7450
1500	2.5632	3.0110	5.5737	4.5391
2000	3.4456	4.0716	6.8927	5.6562
2500	4.4568	5.2310	8.3774	6.8423
3000	5.6921	6.5348	9.8079	8.0871
3500	6.9777	7.7860	11.3311	9.5231
4000	8.4925	9.1731	12.9088	11.1117
4500	9.9494	10.7587	10.2716	10.4297
5000	11.4494	12.3351	11.6951	12.0312

Table 7.2 MAE of the predicted positions of a crossing vehicle based on different sigma

The plot of the values (Figure 7.17) shows that there is nearly a linear increase of the MAE over the whole prediction horizon. The only exceptions are the two last predicted waypoints of the sigma 1.0 and 5.0 line. This happens at the border of the area of interest, when the vehicle almost left this area. If the standard deviation of the input is too large the last waypoints of the three or two last prediction sets are out of that area and it is not able to compute reasonable results. Not considering these unreasonable results, leads to the sudden drop of the MAE value. Furthermore, the fact that the sigma 1.0 MAE are worse, compared to the sigma 5.0 values attracts our attention.

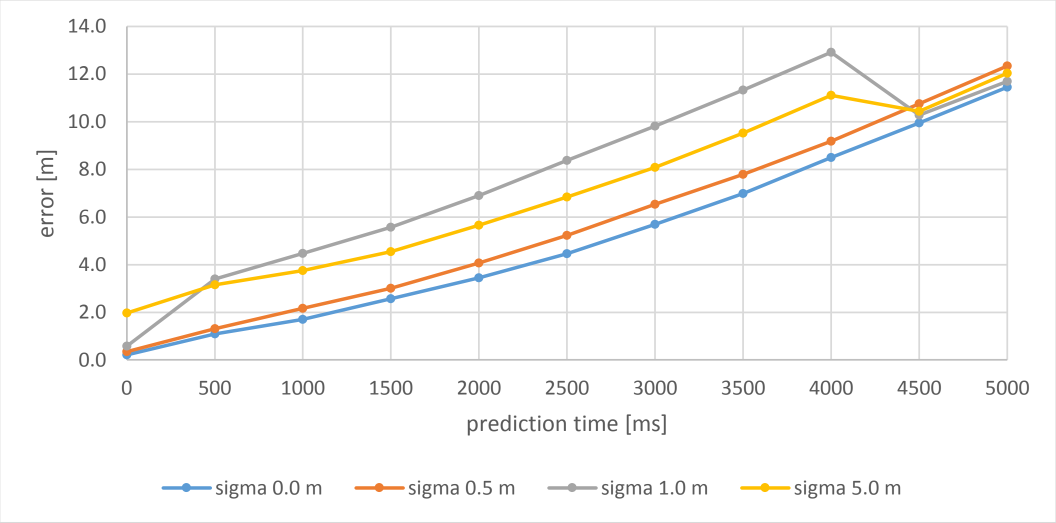


Figure 7.17 MAE of the predicted positions of a crossing vehicle

Figure 7.18 displays the RMSE of the prediction result of the crossing vehicle and provides an explanation. The RMSE of sigma 1.0 results are smaller than the ones of sigma 5.0. The interpretation is that the sigma 1.0 errors are continuously higher than the ones of sigma 5.0. However, the errors of sigma 5.0 have some larger values, which enlarge the RMSE much more than the errors of the sigma 1.0 line.

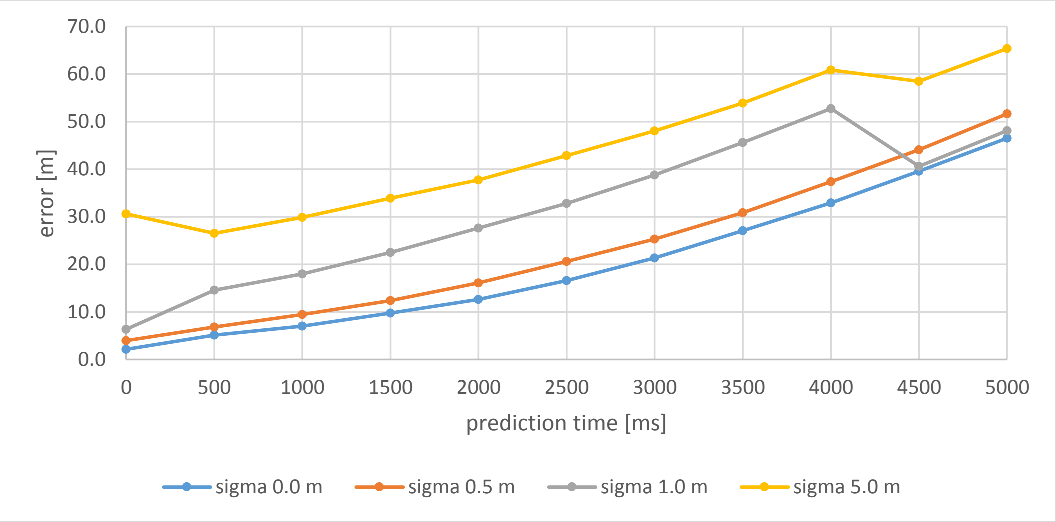


Figure 7.18 RMSE of the predicted positions of a crossing vehicle

Different to the lateral and longitudinal position values, which are fed into the system based on the microscope traffic simulation, the speed values extracted out of VISSIM are not modified. This means that the speed computed in the VISSIM simulation is just brought into the correct message format to deliver it to the IRIS-System. This is also the explanation for the rather small errors in the beginning of the prediction (time step 0) regardless of the sigma of the position value, as Table 7.3 shows. This is the advantage of a vehicle transmitting the direct speed itself. In case the IRIS-System would compute the speed by itself using consecutive positions, the error in the beginning would increase.

Prediction Step [ms]	**Speed [meter/sec] --- Mean Absolute Error**			
	sigma 0.0 m	**sigma 0.5 m**	**sigma 1.0 m**	**sigma 5.0 m**
0	0.0049	0.0050	0.0049	0.0050
500	0.0544	0.0531	0.0571	0.0526
1000	0.1097	0.1093	0.1140	0.1087
1500	0.1622	0.1619	0.1649	0.1624
2000	0.2180	0.2145	0.2196	0.2201
2500	0.2670	0.2667	0.2707	0.2710
3000	0.3160	0.3199	0.3246	0.3217
3500	0.3637	0.3686	0.3743	0.3682
4000	0.4127	0.4188	0.4236	0.4179
4500	0.4588	0.4647	0.4612	0.4612
5000	0.5065	0.5099	0.5062	0.5096

Table 7.3 MAE of the predicted speed of a crossing vehicle

The plot of the values of Table 7.3 in Figure 7.19 shows that there is an increasing linear error going up to 0.5 m/s (1.8 km/h) with a maximum error of 0.6 m/s (2.16 km/h). This error seems to be rather small compared to the error which was observed analyzing the prediction of the position. Broken down to the first prediction step this is an error of 1.0 to more than 3.0 m compared to 5 cm/s. Remember, the position values are altered in their accuracy whereas the speeds are not. At the last prediction step at 5000 ms the errors are about 12.0 m in the position (see last row of Table 7.2) and 0.5 m/s in the speed as Table 7.3 reports.

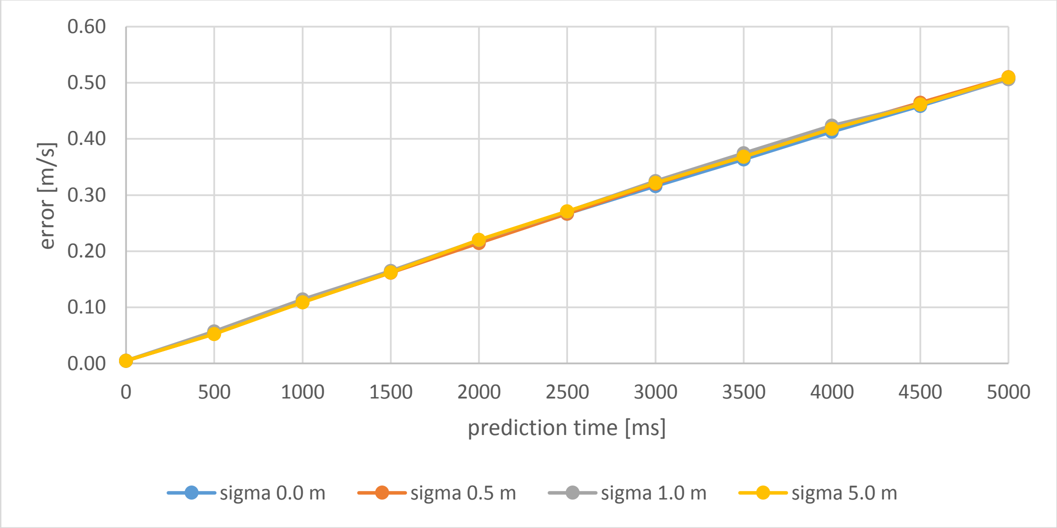


Figure 7.19 MAE of the predicted speed of a crossing vehicle

Looking at in more detail, these values are not surprising. The distance the vehicle has to travel and the future speed values are both based on the typical speed of the reference track or at the required speed. Therefore, the error values are also in line with each other. Looking at the error values again, there is an error of about 12 m in the position. This is the value one gets taking the average speed of the prediction step 0 to 4500 at multiplying with the size of the prediction horizon. For the 5.0 m standard deviation this is 2.39 m/s over 5 s resulting in 11.94 m error in position. This it is not exactly the same value because average values were used to compute the position error based on the speed value error and the positions are matched to the reference track, which also leads to an error. Even in terms of its speed value the error seems to be rather small; the correlation analysis for the speed shows that there is an evident drop of the correlation coefficient (Figure 7.20). At the previous two prediction steps, there was hardly any correlation at all anymore. But these errors are independent of the standard deviation of the position values.

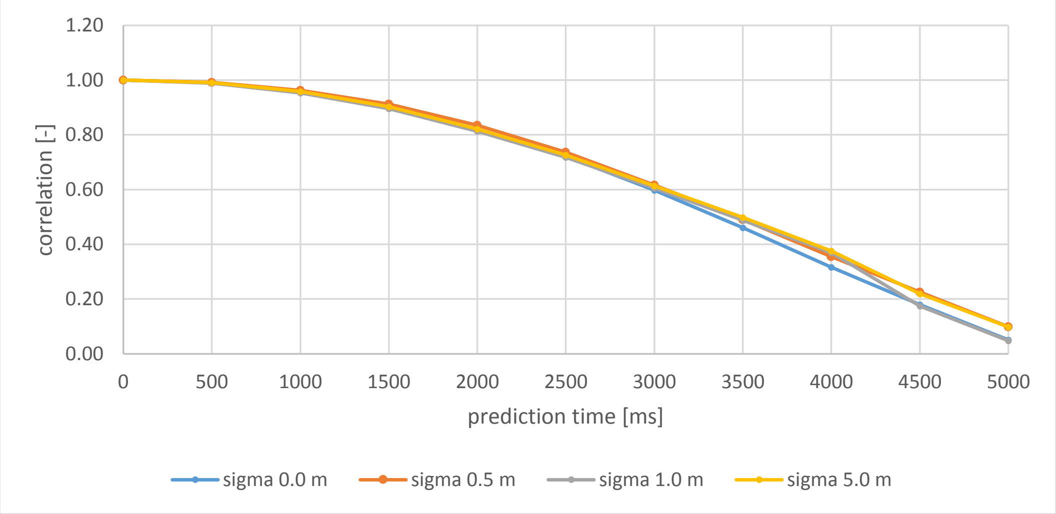


Figure 7.20 COR of the speed values of a crossing vehicle

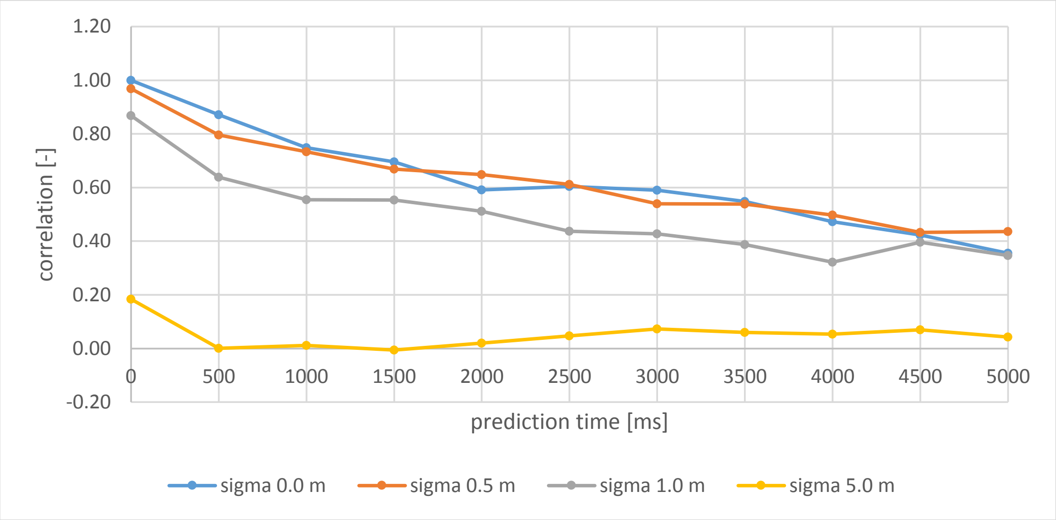


Figure 7.21 COR of the travelled distance of a crossing vehicle

Figure 7.21 shows the correlation coefficient of the travelled distance of the crossing vehicle. Here the influence of the standard deviation is evident. The 5.0 m deviation only leads to a

0.20 correlation value right at the beginning. But for all deviations the decrease of the correlation coefficient is common. These results show the strong dependency of the prediction of the required speed and typical speed values. These values need to be adjusted based on real measures at the intersection the system is to be installed.

Different Length of Prediction Time Step and Constant Standard Deviation

In this test case, the standard deviation of the vehicle's position keeps a constant value of 0.5 m, but instead the length of the prediction time step is altered. The total number of time steps is still 10. That means having a length of the prediction time step of 250 ms the prediction horizon is 2.5 s, at 500 ms it raises up to 5 s and reaches 10 s at a time step length of 1000 ms. Table 7.4 presents the mean absolute error for the crossing vehicle based on the prediction with the three different lengths of the time step.

The MAE at the starting point of the prediction is nearly the same for each prediction setting. For the three settings, the MAE approximately raises in a linear way, except for the 1000 ms prediction step as Figure 7.22 shows. The reason for the dislinearity of the grey line is that the prediction reaches beyond the area of interest and therefore no VISSIM value is available for comparison.

Prediction Step	**Absolute Position [meter] --- Mean Absolute Error**		
	time step 0.25	**time step 0.5**	**time step 1.0**
0	0.2970	0.3494	0.3058
1	1.3409	1.3166	2.7452
2	2.2383	2.1653	4.8650
3	2.1163	3.0110	7.3266
4	3.0965	4.0716	10.3409
5	2.9685	5.2310	13.5087
6	4.0963	6.5348	12.2950
7	3.9855	7.7860	13.1526
8	5.3337	9.1731	14.2411
9	5.1721	10.7587	13.1494
10	6.6462	12.3351	13.9796

Table 7.4 MAE of the predicted positions of a crossing vehicle based on different length of the prediction time step

Looking at the prediction horizon, the values in a 2-second prediction (the light red box highlighted in Table 7.4) show that the MAE at prediction step 8 of the 0.25-second time stepped is 5.3337 m, for the 0.5-second resolution at prediction step 4 is 4.0716 m and for the 1-second time stepped it is 4.8650 m. This shows that the smaller prediction resolution does not necessarily lead to a better result. The 0.5-second time stepped resolution shows a MAE of 5.2310 m at the prediction step 5. This test gave the evidence that the 1-second resolution has a large prediction horizon but leads also to large errors. The small resolution of 0.25 s does not lead to smaller errors than the 0.5 resolution prediction, but has the disadvantage of a shorter horizon. Therefore, the length of 500 ms is a suitable choice.

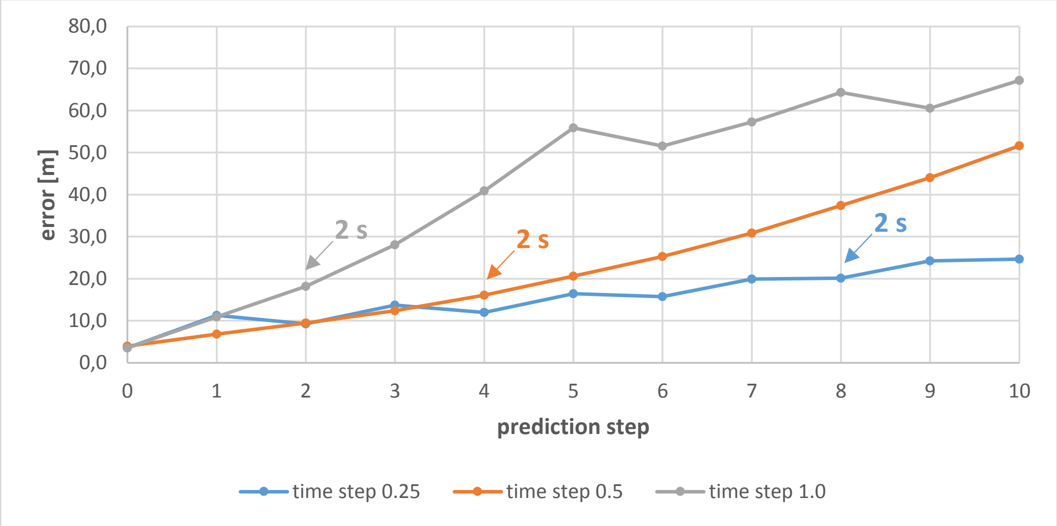


Figure 7.22 MAE of the predicted positions of a crossing vehicle

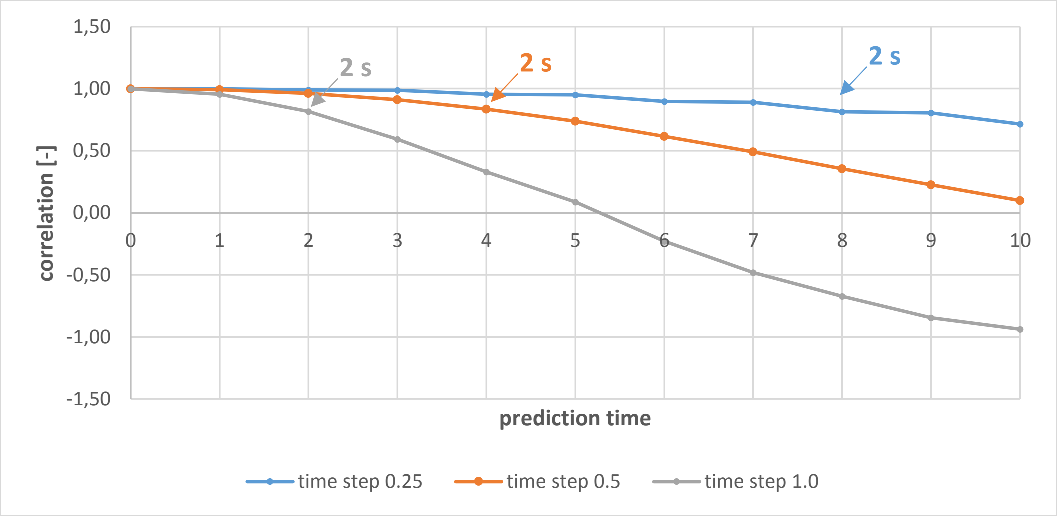


Figure 7.23 COR of the speed of a crossing vehicle

The correlation coefficient of the speed and the travelled distance for the three prediction resolutions supports the choice of a 500 ms length of a prediction time step. As Figure 7.23 and Figure 7.24 display, the speed and travelled distance correlation reaches similar values for the same prediction horizon. However, for the 1.0-second resolution, the speed correlation even reaches a negative value after 5 s. The explanation for this observation is again that the trajectory reaches beyond the area of interest. For the travelled distance, the 1.0-second shows the lowest correlation. Nevertheless, the 0.25 and 0.5 resolutions are nearly identical. The results of the 0.5 resolution are even better than the results for the 0.25 resolution up to the fifth prediction step.

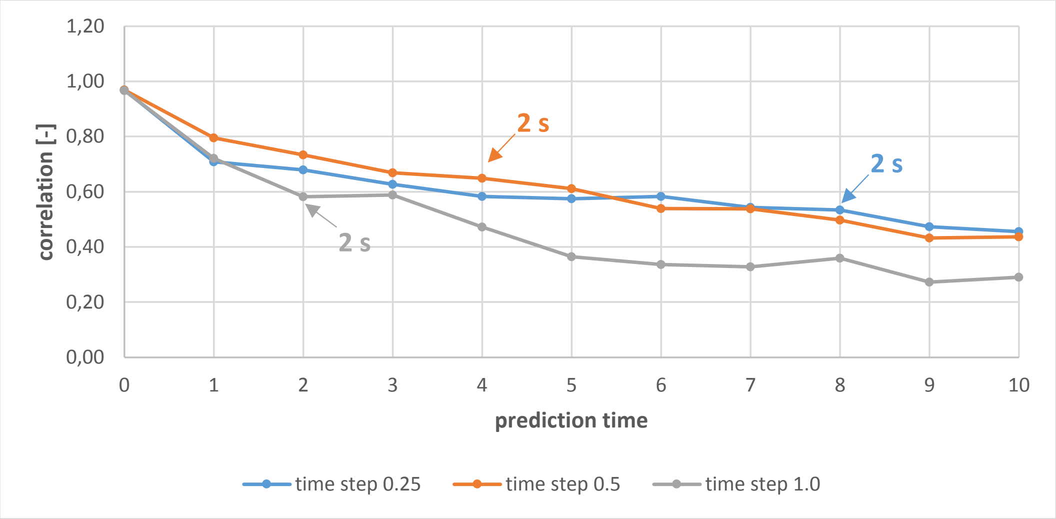


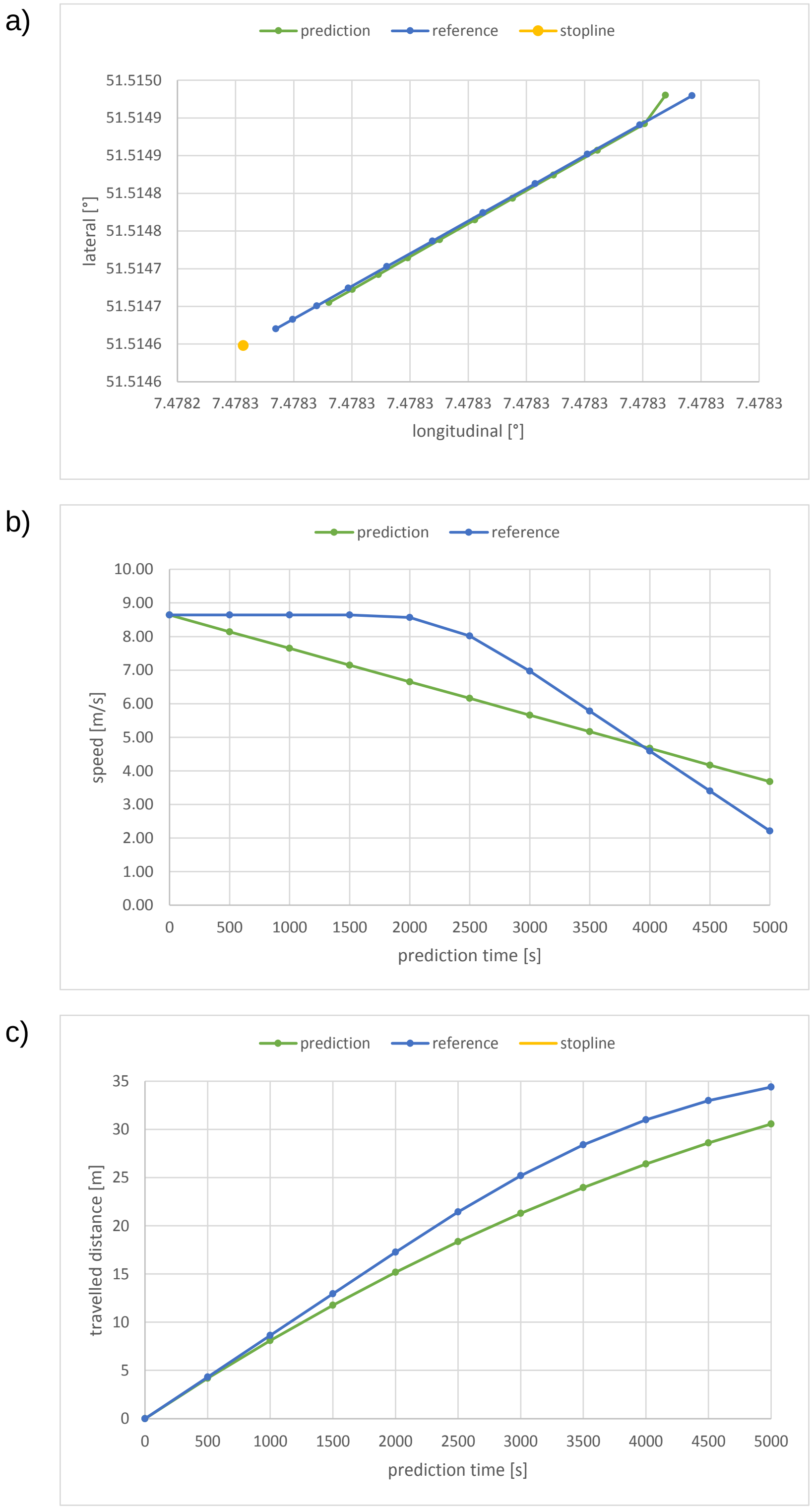
Figure 7.24 COR of the travelled distance of a crossing vehicle

Conclusion

The prediction of the movement of the vehicles was analyzed in a lateral point of view. The results of the prediction steps for the same prediction horizon in the scenario ‘crossing the intersection’ were compared by using the mean absolute error, the root mean squared error, the maximum absolute error and the correlation index as error measures. The basic settings for the prediction varied: the length of the prediction interval and the standard deviation of the positions of the vehicles. For this basic scenario, the error measures indicated good results for a prediction time step of 500 ms and a positioning standard deviation of 0.5 m. The test also showed the importance of the dependency of the prediction on the typical and required speed. Observations of the typical speed and required speed at the real intersection the IRIS-System planned to be installed are necessary to tune the system. The further the predicted waypoint is in the future, the larger the errors get, because the influence of the starting point of the trajectory, which is based on no predicted data from the vehicle, shrinks and the influence of the required speed estimations becomes more. Nevertheless, based on these first test results, the basic parameters for the tests were set to a length of the prediction step of 500 ms and a standard deviation of 0.5 m for the vehicles’ position. These settings are chosen to be constant for all the following tests.

Longitudinal point of view: different scenarios

Stopping at the Red Light



Starting point of the prediction and the predicted positions (green line) compared to the reference trajectory (blue line) at the same point in time.

Vehicle is approaching the yellow point (stop line)

The reference speed (blue line) and the speed of the prediction (green line) for each prediction time step.

The travelled distance of the reference trajectory (blue line) and the predicted trajectory (green line).

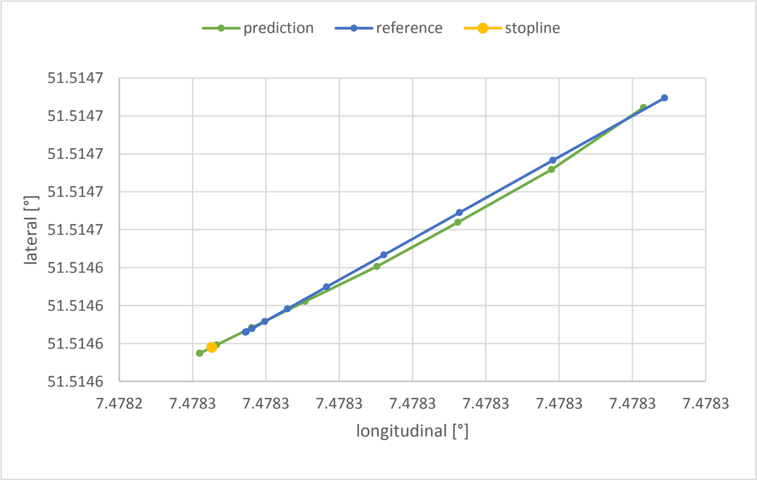
Figure 7.25 Reference and predicted trajectory of an approaching vehicle at the red light

Diagram a) in Figure 7.25 displays the reference and the predicted trajectory via the prediction horizon of 5 s. The second diagram shows the reference speed versus the predicted speed of the vehicle and diagram c) reports the reference and the predicted travelled distance of the vehicle. These pictures represent a snapshot of one certain moment of the predicted vehicle trajectory. There are 11 waypoints, with the first point being the starting moment of the prediction and the 10 following points being the single prediction steps.

Three phases are investigated for testing the stopping at the red light: approaching, stopping and starting as the lights turned green again. Figure 7.25 to Figure 7.27 depicted these three phases. Figure 7.25 shows the reference and predicted trajectory for the approaching vehicle. In the moment of the snapshot - the point “now” - the vehicle is 6.4 s before the stop line. This means that during the prediction, the stop line will not be reached. Nevertheless, the pictures show that the predicted vehicle (green) anticipates the red light at the stop line as it starts to decelerate. This is because the vehicle is already within the awareness distance as it is closer than 50 m to the stop line. However, the reference vehicle (blue) starts to decelerate later than the predicted one. In most of the prediction time steps, the reference vehicle is faster than the predicted. Therefore, the prediction algorithm underestimates the travelled distance. A possibility to tune this behavior of the algorithm is to reduce the awareness distance, so the presence of the red light at the stop line influences the prediction of the vehicle’s trajectory later.

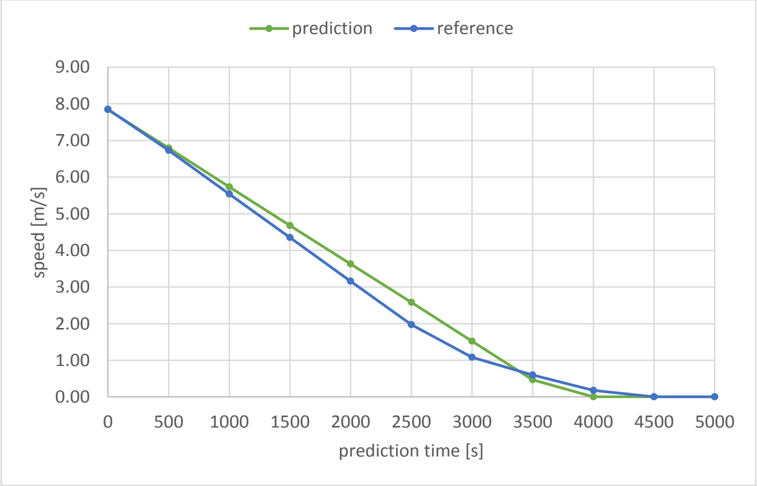
Figure 7.26 indicates the reference and predicted trajectory for a stopping vehicle at the red light. The point “now” is 4 s before the vehicle reaches the red light. The deceleration of the predicted vehicle is now much more in line with the one of the reference vehicle. In addition, the predicted vehicle stops in time at the red light at the prediction time step 7 (3500 ms).

a)



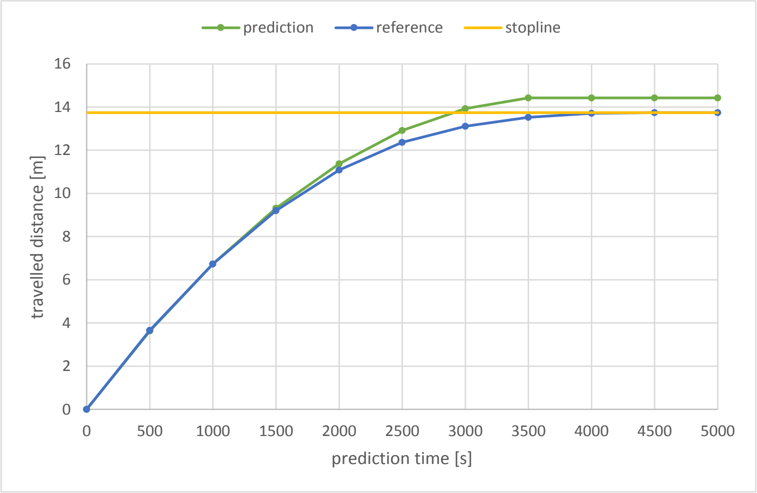
Starting point of the prediction and the predicted positions (green line) compared to the reference trajectory (blue line) at the same point in time.

b)



The reference speed (blue line) and the speed of the prediction (green line) for each prediction time step.

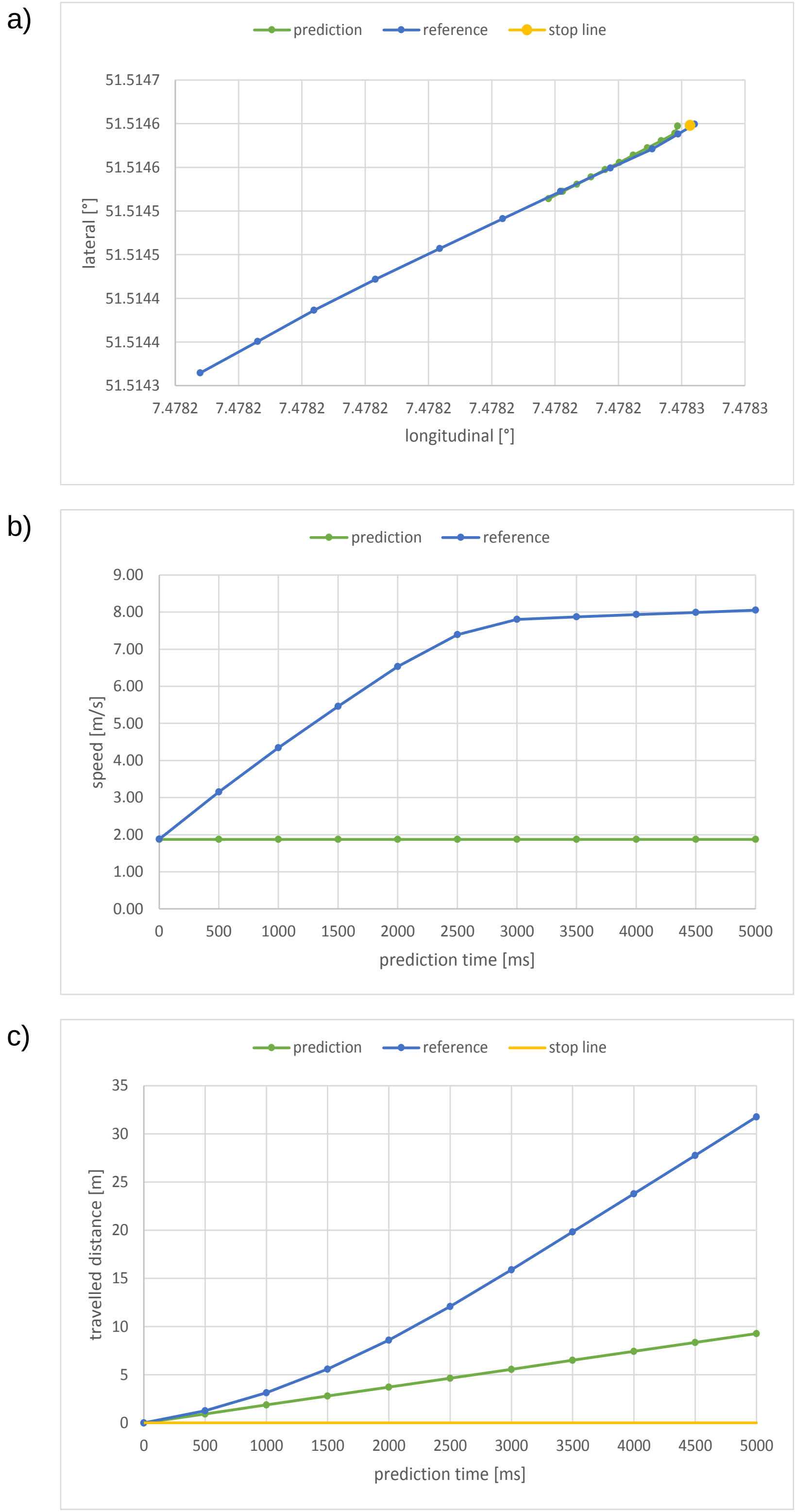
c)



The travelled distance of the reference trajectory (blue line) and the predicted trajectory (green line).

The yellow line represents the stop line.

Figure 7.26 Reference and predicted trajectory of a stopping vehicle at the red light



Starting point of the prediction and the predicted positions (green line) compared to the reference trajectory (blue line) at the same point in time.

The reference speed (blue line) and the speed of the prediction (green line) for each prediction time step.

The travelled distance of the reference trajectory (blue line) and the predicted trajectory (green line).

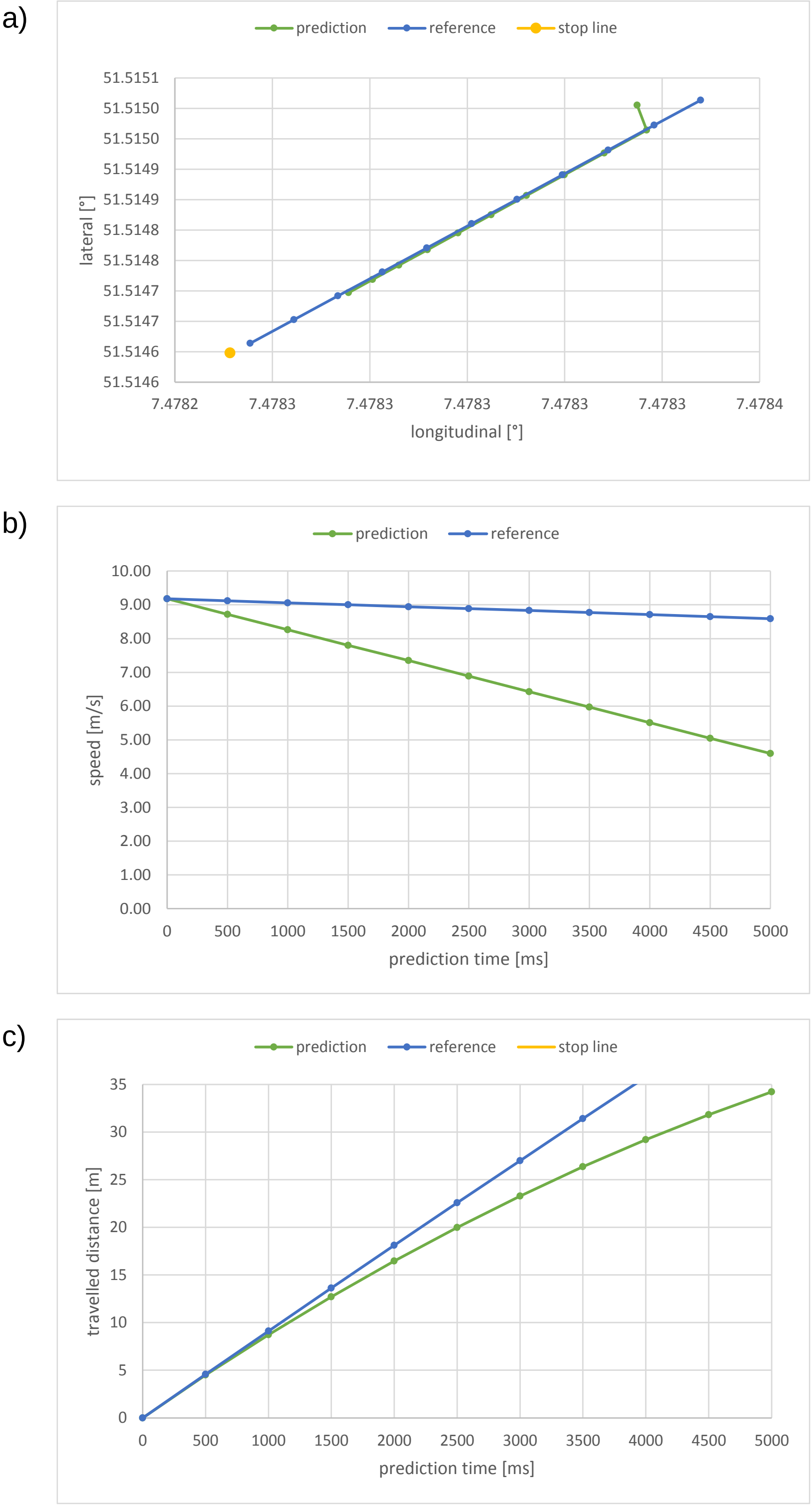
The yellow line represents the stop line.

Figure 7.27 Reference and predicted trajectory of a starting vehicle after stopping at the red light

Figure 7.27 shows the reference and predicted trajectory of the accelerating vehicle after the stop at the red light. The time of the snapshot is matching the time the light turns green. The reference vehicle accelerates until reaching the desired speed. However, throughout the whole prediction horizon the prediction assigns a constant speed to the green vehicle. Therefore, the travelled distance is underestimated and the computed positions deviate from the reference positions. At the last prediction time step, the total error is more than 22 m. This drawback of the algorithm and cannot be tuned by changing parameters, only by adjusting the algorithm itself.

Violating the Red Light

The following tables show the results of the predictions about vehicles violating the red light. Figure 7.28 depicts the situation 5 s before the vehicle will reach the stop line. The pictures show that the reference vehicle is not reacting to the red light and so it does not reduce its speed. However, the predicted trajectory does react to the red light and starts decelerating. This is because the algorithm for the prediction stays within the traffic rules as long as possible.



Starting point of the prediction and the predicted positions (green line) compared to the reference trajectory (blue line) at the same point in time.

Vehicle is approaching the yellow point (stop line)

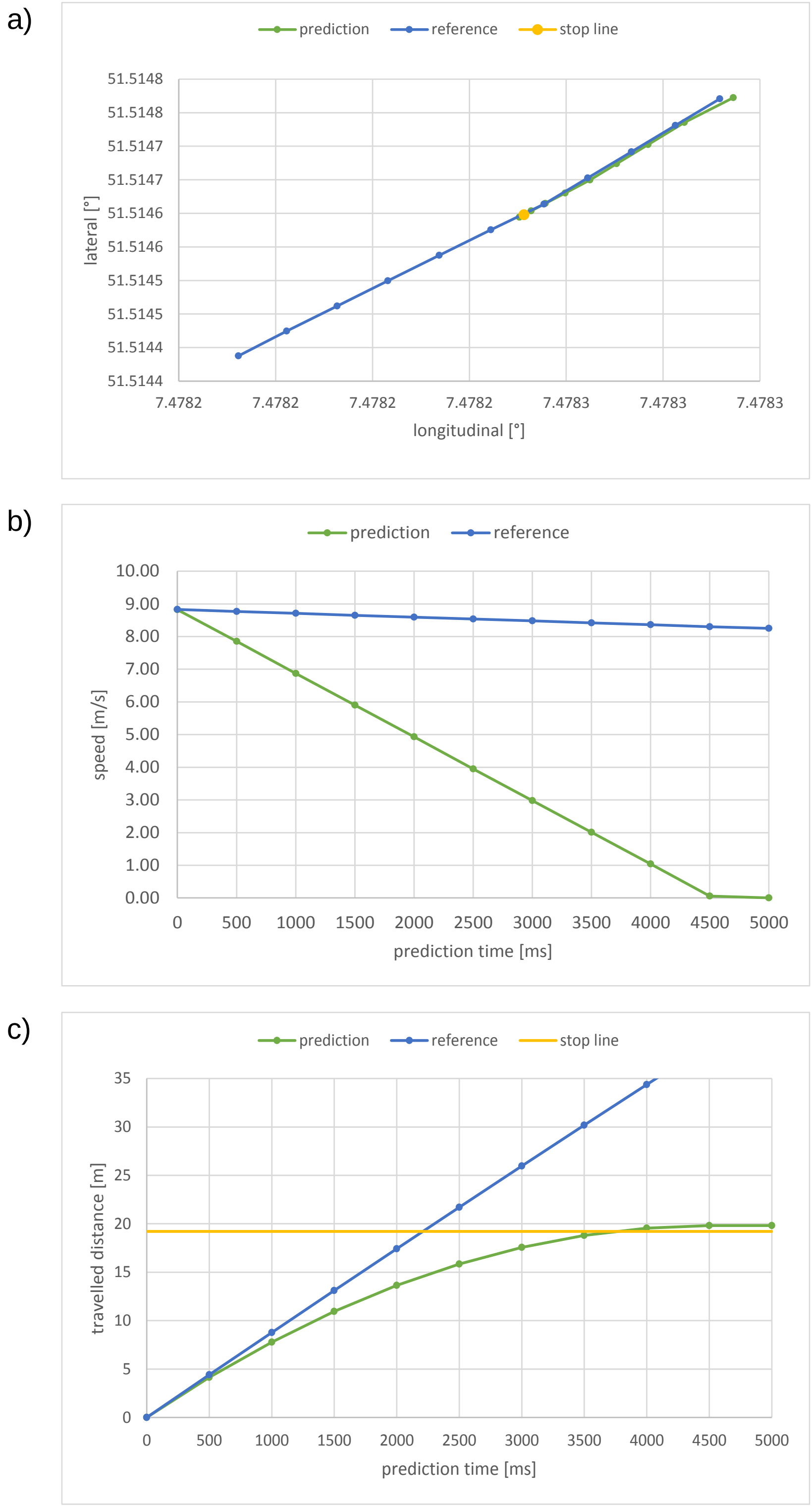
The reference speed (blue line) and the speed of the prediction (green line) for each prediction time step.

The travelled distance of the reference trajectory (blue line) and the predicted trajectory (green line).

The yellow line represents the stop line.

Figure 7.28 Reference and predicted trajectory of an approaching vehicle violating the red light

The pictures in Figure 7.29 show the situation in which the vehicle is 2 s before reaching the stop line. The reference vehicle is passing the red light, but the prediction algorithm makes the green vehicle stop at the red light. This leads to a maximum error in the position of 23 m in the last prediction step. The third picture depicts this behavior of the prediction very distinctly.



Starting point of the prediction and the predicted positions (green line) compared to the reference trajectory (blue line) at the same point in time.

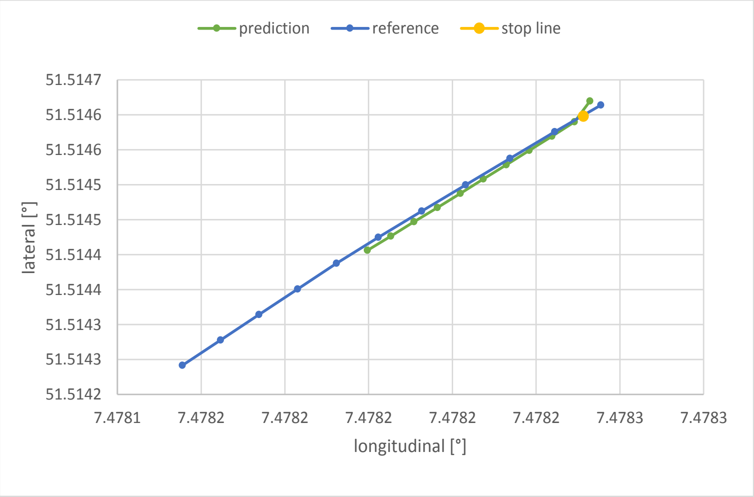
Reference vehicle is violating the red light.

The reference speed (blue line) and the speed of the prediction (green line) for each prediction time step.

The travelled distance of the reference trajectory (blue line) and the predicted trajectory (green line).

The yellow line represents the stop line.

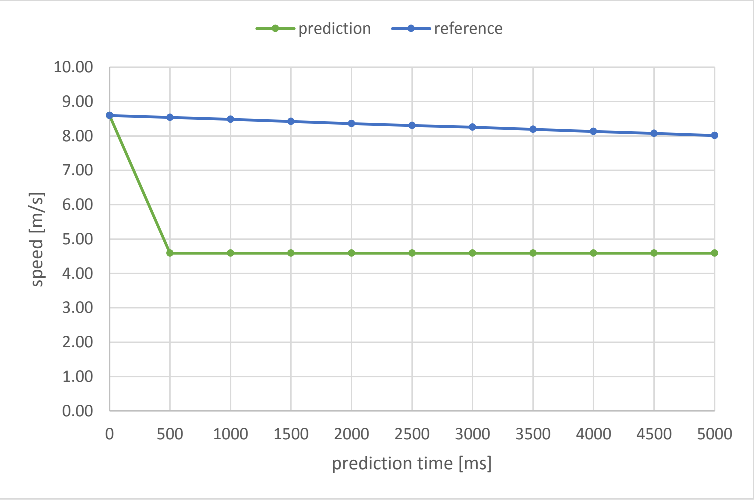
Figure 7.29 Reference and predicted trajectory of a vehicle right before violating the red light a)



The starting point of the prediction and the predicted positions (green line) compared to the reference trajectory (blue line) at the same point in time.

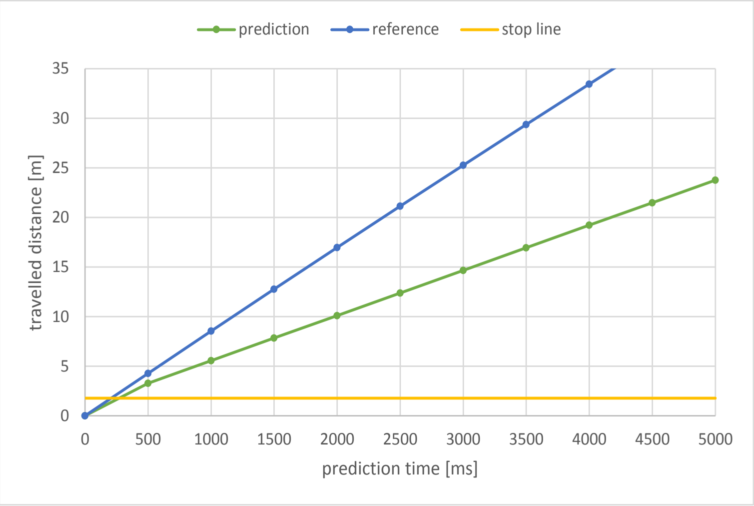
Both vehicles passed the stop line.

b)



The reference speed (blue line) and the speed of the prediction (green line) for each prediction time step.

c)



The travelled distance of the reference trajectory (blue line) and the predicted trajectory (green line).

The yellow line represents the stop line.

Figure 7.30 Reference and predicted trajectory of a vehicle right after violating the red light

Figure 7.30 presents the prediction of the situation at the moment of the crossing of the stop line. From that point on, the violation is obvious and therefore the predicted vehicle starts to move again. The speed is still underestimated at this point. This is adjusted starting the next set of prediction points. (No picture).

Enable the algorithm to estimate the red-light violation in a more realistic way, the speed and the change in speed of the information sent by the vehicle via the VANET needs to be considered. This information could be used to overrule the required speed of the resistance point “Red Light at Stop Line”. This would lead to the fact that the predicted vehicle does not stop at the red light. The open question is still at what point in time the required speed needs to be overruled. A car approaching with 50 km/h goes 13.88 m a second. Therefore, 1-1.5 s could be a valid starting point for that parameter.

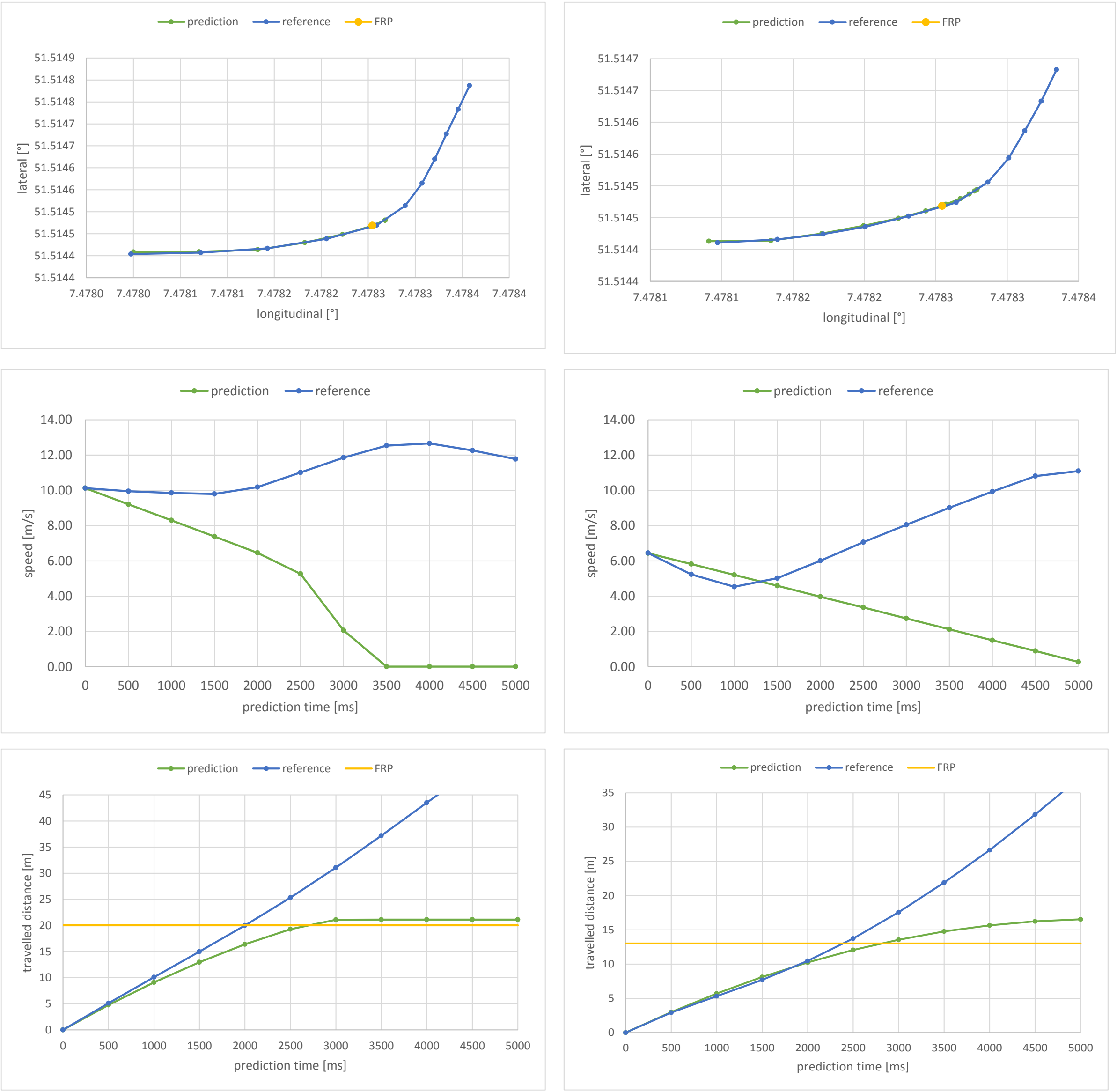
Vehicle Turning Left

This scenario is representative of the prediction using the fixed resistance point (FRP) defined by two intersecting reference tracks. If there is no other vehicle oncoming the influence of that FRP should be zero. In case there is another vehicle approaching, the movement of the turning vehicle needs to be adapted. The graphs in Figure 7.31 show the results of the prediction in the case without (left series of graphs) and with (right series of graphs) an oncoming vehicle. The pictures depict the reference (blue line) and the predicted trajectory (green line), the speed and the travelled distance. The yellow line or point represents the resistance point.

Figure 7.31 Oncoming vehicle while turning left – about 5 seconds before the resistance point

In the case above (Figure 7.31) only the last predicted point touches the FRP. There is a obvious difference in the two predicted trajectories. In both cases the predicted speed values stay at a level of 8 m/s. If there is an oncoming vehicle, the reference vehicle decelerates already, but not the predicted vehicle. The discontinuity at the beginning of the prediction is since at the first point the position is received by the VANET; the 10 following points are predicted on the RT. The slight mismatching of the VISSIM network and the representation of the intersection with the reference tracks lead to this phenomenon.

About two seconds from the resistance point (graphs of Figure 7.32), the prediction should lead to a trajectory with a speed being at the level of the typical speed, which is about 40 km/h while turning left. This is not the case. Instead, the speed is reduced further in the predicted trajectory than in the case of the oncoming vehicle. This is a shortcoming of the prediction algorithm, which has not been solved yet. The consequence of this phenomenon is that there might be a warning when the vehicle is not in line with the required speed. This could lead to unnecessary warnings making IRIS inconvenient for drivers. The testing of the threat assessment in paragraph 7.1.4 will provide more knowledge on this. Furthermore, the picture shows that the prediction is still decelerating while the VISSIM vehicle is already accelerating again after the oncoming vehicle has passed. The IRIS-System is not able to reproduce this detailed behavior at the state of development.

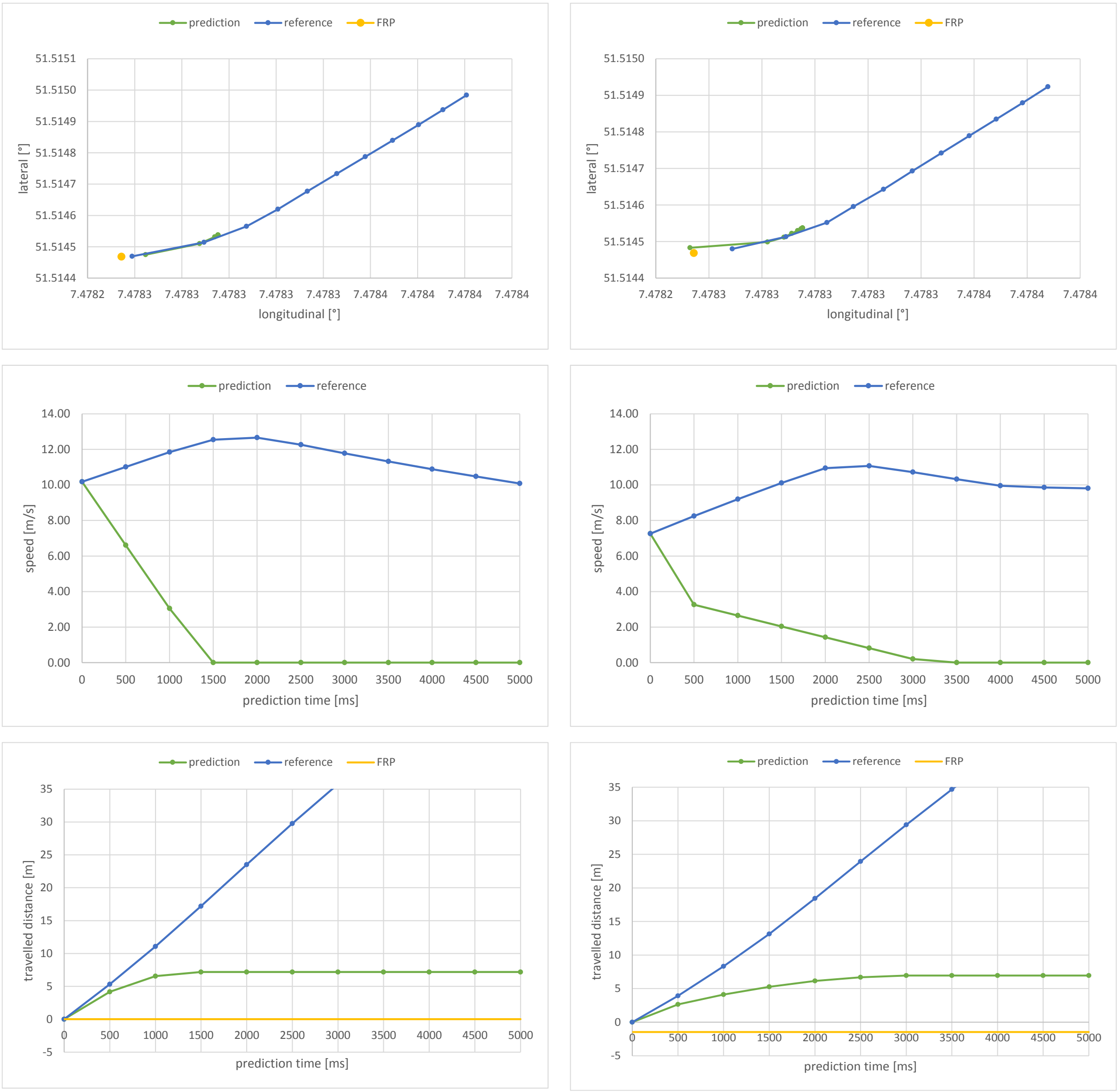


Without an oncoming conflicting vehicle

With an oncoming conflicting vehicle

Figure 7.32 Oncoming vehicle while turning left – about 2 seconds before the resistance point

The last set of graphs (Figure 7.33) shows the situation right after the vehicle has passed the resistance point. In addition, here the prediction is slower than reality. The RP still influences the prediction as the vehicle decelerates instead of accelerating. Five hundred milliseconds later, the RP loses its influence and the predicted vehicle catches up with reality again (no picture).



Without an oncoming conflicting vehicle

With an oncoming conflicting vehicle

Figure 7.33 Oncoming vehicle while turning left – leaving the resistance point

The situation of two conflicting reference tracks or two conflicting vehicles is the most challenging one. The used concept of the fixed resistance points in this case works up to a certain degree. The system is able to identify critical situations. But, it might also produce false warnings. It is obvious that the RP influences the prediction but not in the precise way the prediction would require for representing the reality exactly.

Following another Vehicle

“Following another vehicle” is modeled using moving resistance points. The leading vehicle represents the moving RP. This RP overrules the required speed of the fixed RPs and the typical speed assigned to the reference track. Figure 7.34 depicts the reference trajectories of the leading vehicle (light blue line) and the following vehicle (orange line). The following vehicle approaches the leading one and keeps nearly the same distance to the leader. This behavior is based on the default settings of the VISSIM car following model. Furthermore, the picture shows three predicted trajectories: one representing the 500 ms prediction step result (dark blue line), one the 1000 ms (grey line) and the last trajectory displays the 5000 ms prediction step outcome (yellow line).

The 500 and 1000 ms trajectories are quite close to the reference line, which is the proof of the correct working algorithm. The trajectories, like a step-function, result from the fact that the speed of the leading vehicle is assigned to the following if the car is close enough. Therefore, it follows in an oscillating manner. And if the following vehicle gets too close it even stops. This effect gets larger the further away into the future the predicted waypoints are. Additionally, the prediction reacts to the leading vehicle with a delay of 5 s. This can lead to errors in the computing of the position up to 20 m. The yellow line clearly displays this fact.

For computing the threat of a situation, the moving resistance points play a minor role, as the important vehicles are the leading ones. However, this concept is very helpful for avoiding the computation of many unreasonable trajectories. For this purpose, the achieved quality is absolutely satisfying.

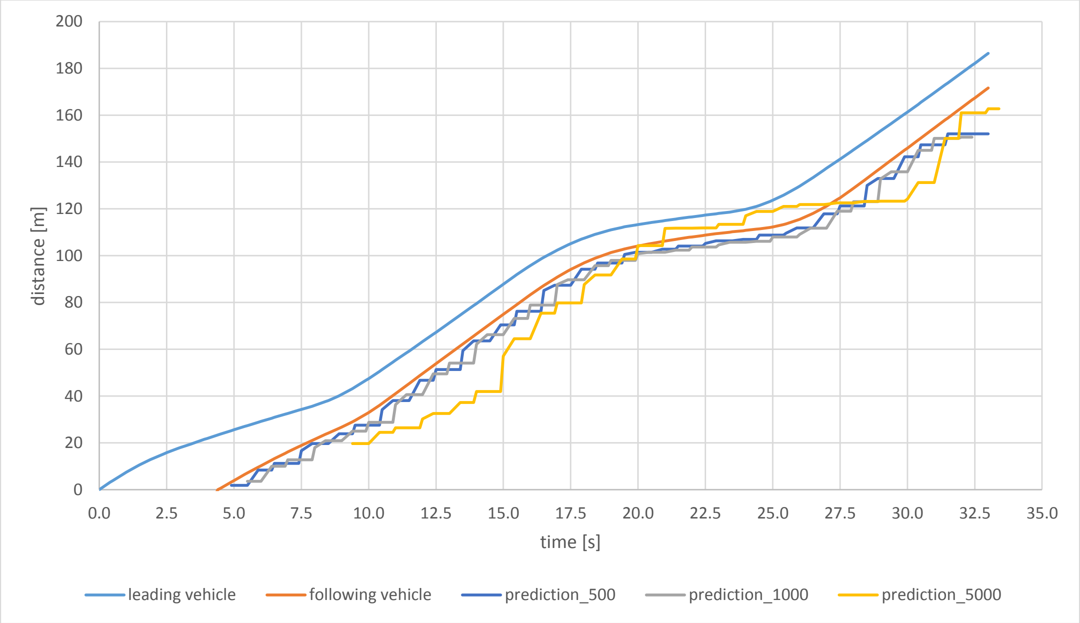


Figure 7.34 Reference and predicted trajectories of leading and following vehicle

Conclusion

By using the longitudinal point of view, the following scenarios were analyzed to test the functionality of the resistance points: stopping at a red light, violating a red light, left turn with and without an oncoming vehicle, as well as following another vehicle. The fixed resistance point at the stop line is linked to the traffic light signal to determine the required speed of the resistances point. In case of stopping at the red light, the prediction is very much in line with the reference trajectory. The deceleration and acceleration process is not as smooth as it is modeled in VISSIM. This could be adjusted by decreasing the driver’s awareness distance to the red light. In the case of violating the red light, the prediction follows the traffic rules fairly long, meaning the predicted vehicle decelerates rather late and quite abruptly in front of the red light. The drawback is that as soon the vehicle starts driving again, the assigned speed for the prediction is too small and constant. That means the prediction does not model the acceleration behavior after starting again in a realistic way. For the prediction of trajectories this is not satisfactory, but for the threat assessment this is irrelevant as there is no scenario dealing with this situation. The unprotected left turn maneuver of the vehicle leaves still a challenge to be addressed. The required speed of the resistance point is related to the approach of another vehicle on the conflicting RT. It turned out that the system still has some troubles to compute the correct required speed. The prediction is rather defensive, meaning it works better slowing down than accelerating to high speed. This fact will lead to unnecessary warnings and needs to be further improved and tested in the future. The modeling of the following car works sufficiently. No cars are piling up. They follow each other, which is sufficient for the IRIS-System.

7.1.4 Testing the Threat Assessment

This section deals with the testing of the last step in the process chain of the IRIS-System, the threat assessment. The implemented threat assessment strategy is applied to the reference trajectory and the predicted trajectory. Doing so, the results of the threat assessment based on the predicted trajectories are compared against the reference trajectory. For that purpose, the scenarios

- violating the red light,
- stopping at the red light and
- unprotected left turn

will be investigated in more detail.

Violating and Stopping at the Red Light

Table 7.5 lists the result of the threat assessment of the predicted trajectory. The table comprises the following columns:

- the relative point in time the prediction is based on,
- the distance to the resistance point (in this case the stop line),
- the time to the resistance point based on the predicted trajectory and
- the required acceleration to meet the required speed.

The green, orange and red boxes indicate whether the result of the threat assessment triggers the transmission of a warning or not. The green margin is for an executed assessment without a warning is necessary. For a safety warning, the deceleration threshold is set to -3 m/s² (orange box) and for the critical warning it is set to -6 m/s² (red boxes).

point in time [s]	**Predicted Trajectory**		
	distance to RP [m]	**time to RP [sec]**	**required deceleration [m/s²]**
0.0	20.35	4.5	-1.96
0.4	18.31	4	-2.19
1.0	13.01	3	-2.9
1.4	10.15	2	-4.33
2.0	3.97	0.65	-13.27

Table 7.5 Threat assessment – red light violation – predicted trajectory

The first three assessments in Table 7.5 lead to decelerations below the threshold of -3 m/s² and therefore the algorithm does not trigger a warning. The vehicle is more than 3 s away from the stop line. Two seconds before the stop line the required deceleration of -4.33 m/s² triggers a safety message. The critical warning issued 0.65 s before the stop line is too late to make the driver stop before the line. A potential accident can only be mitigated at this state. An automatic forced braking action could provide benefit at this point, but was not foreseen to implement it in the vehicles. However, there was already a warning before to alert the driver. Moreover, by changing the threshold for example to -2.5 m/s² the first warning is triggered 3 s before the stop line in that case.

It is important to keep in mind that the computation of the time to the resistance point and the required deceleration is based on the predicted trajectory. The real vehicle or reference vehicle simulated in VISSIM is violating the red light at a higher speed in this case. The reason for this is that the prediction assumes that the driver sticks to the traffic rules. This condition leads to the fact that the predicted trajectory represents a slowing down vehicle in front of the red light up to a complete stop. The Figure 7.35 illustrates this concept in a very good way. It shows the situation at time point 0.4 s, 18.31 m before the stop line. During the prediction, the speed drops to the required speed of the resistance point, which in the case of the red light is zero. Up to that point the system still assumes that the vehicle might stop in front of the red light considering a maximum deceleration capacity of -8 m/s². However, the reference vehicle keeps on going at a high speed. This leads to a real time to the RP of about 2 s. This is half of the time the predicted vehicle needs to reach the stop line.

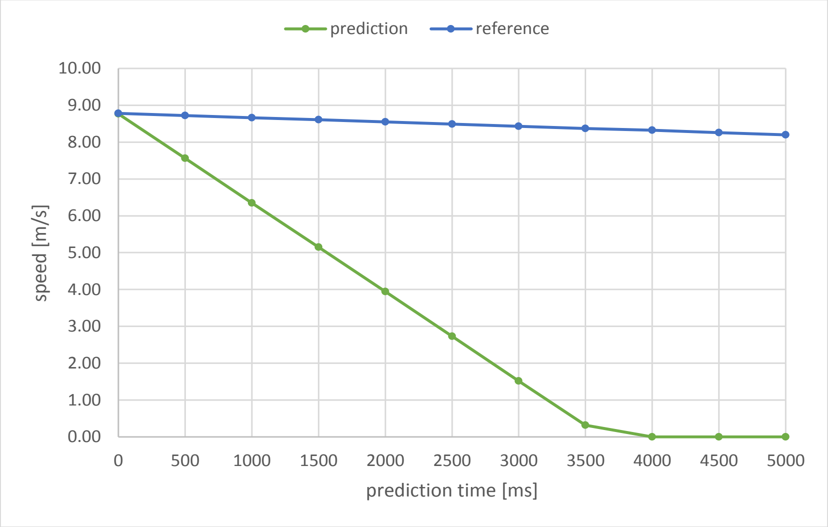


Figure 7.35 Threat assessment – red light violation – speed profile 18.31 m before the stop line

Figure 7.36 depicts the point in time 2.0 s in which the vehicle is 3.97 m in front of the stop line. Stopping a real vehicle before the line is impossible at this stage. In addition, the prediction is not able anymore to make the vehicle stop, because the maximum deceleration capacity is exceeded. Therefore, the prediction also violates the red light. However, a warning is issued. This critical warning can only mitigate the impact of a potential accident if the driver starts braking immediately after recognizing the received message or automatically braking is forced.

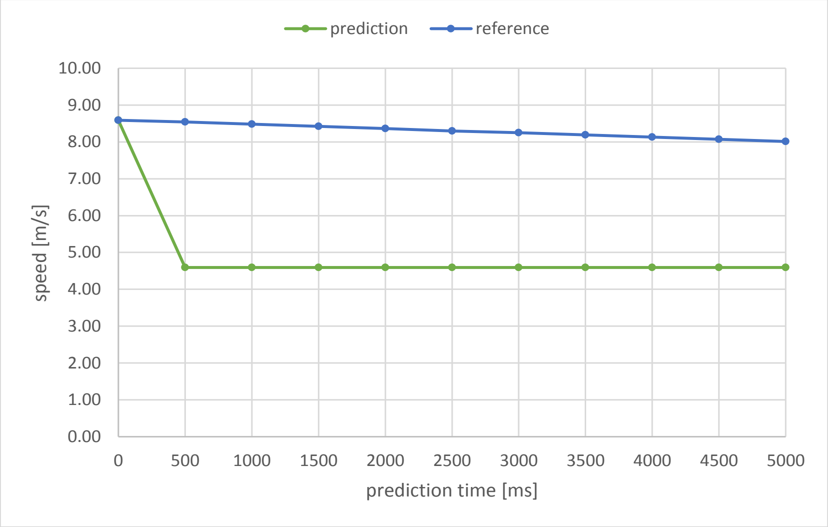
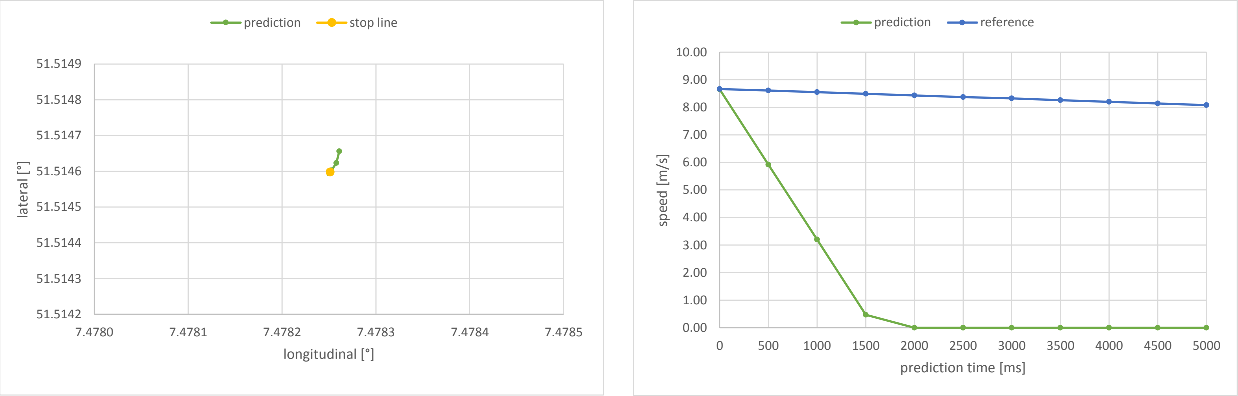


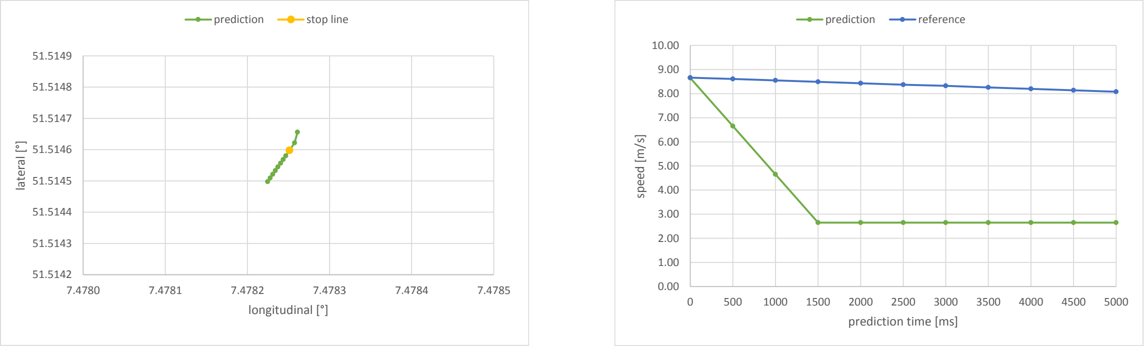
Figure 7.36 Threat assessment – red light violation – speed profile 3.97 m before the stop line

To make the system generate warnings at a more appropriate point in time, three countermeasures are possible: Firstly, changing the thresholds to issue a warning already at lower required deceleration. Secondly, changing the maximum deceleration parameter for the prediction algorithm to prevent the vehicle from decelerating too hard right before the red light or any other RP requiring low speed values. Thirdly, changing the prediction algorithm in a way that it recognizes that the prediction does not fit the real situation at an earlier stage.



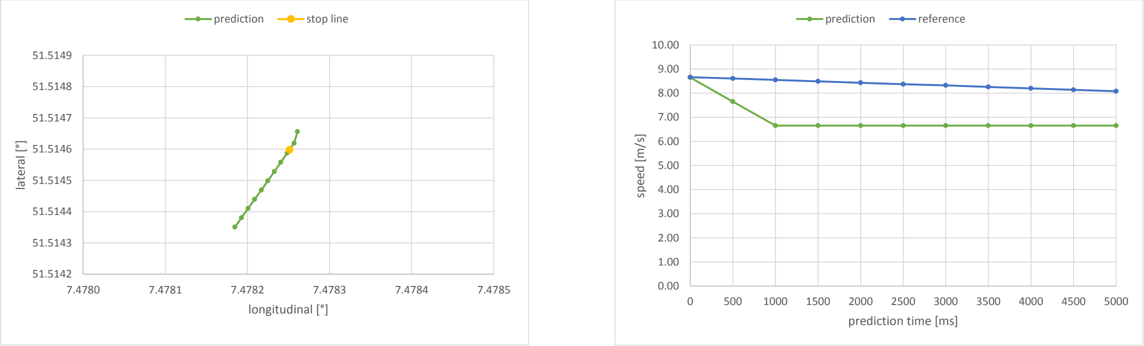
predicted trajectory speed profile

Figure 7.37 Predicted trajectories – red light violation – speed profiles at a deceleration capacity of - 8 m/s²



predicted trajectory speed profile

Figure 7.38 Predicted trajectories – red light violation – speed profiles at a deceleration capacity of - 4 m/s²



predicted trajectory speed profile

Figure 7.39 Predicted trajectories – red light violation – speed profiles at a deceleration capacity of - 2 m/s²

For the last option, one possibility would be to compare the result of the prediction, one or more time steps done before, with the real trajectory received via the VANET. If there is a huge mismatch of the real speed to the predicted speed, a correction factor should include this fact to adjust the predicted trajectory to be closer to the reference trajectory. This countermeasure cannot be pursued by only changing the parameters of the algorithm. Therefore, the second countermeasure, changes the deceleration capacity used to improve the results.

The graphs shown in Figure 7.37, Figure 7.38 and Figure 7.39 represents the results of the second strategy. Diagram a) shows the speed profile at a deceleration capacity of 8 m/s² - as in the example above. In diagram b) the declaration capacity is reduced to 4 m/s² and in diagram c) to 2 m/s². The snapshot of the trajectory prediction is always taken at the same point in time, at 1.4 s. This is 10.15 m before the stop line. Applying -8 m/s² deceleration capacity the vehicle stops in front of the red light. With -4 m/s² and -2 m/s², the vehicle violates the red light but slows down according to the deceleration capacity.

Table 7.6 sums up the results of the threat assessment for the three deceleration cases. The distance to the RP “d2RP_t0” and the speed “v_t0” at the beginning of the trajectory at the point “NOW”, which is the last point received from the VANET is similar for all three cases. The column “d2RP_t10” reports the distance to the RP from the last point of the predicted trajectory. A negative value means that the vehicle is already beyond the RP. The distance to the RP in the last point of the prediction “t10” never becomes zero because of the half vehicle length. The center is in the middle of the vehicle and the prediction is based on this point. Because of the dimension of the vehicle, it stops about the half vehicle length before the stop line. Keep in mind that the results are based on the values received from the VANET. Each point t0 is a new received value. Therefore, there could appear some inconsistencies.

point in time [s]	**d2RP_t0 [m]**	**v_t0 [m/s]**	**- 8 m/s²**			**- 4 m/s²**			**- 2 m/s²**		
			d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s²]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s²]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s²]
0.0	20.35	8.82	2.12	4.5	-1.96	2.12	4.5	-1.96	-1.00	4.45	-1.98
0.4	18.31	8.77	2.15	4	-2.19	2.15	4	-2.19	-4.54	3.36	-2.61
1.0	13.01	8.71	2.10	3	-2.9	2.10	3	-2.9	-14.54	1.92	-4.53
1.4	10.15	8.65	2.14	2	-4.33	-7.60	2.13	-4.06	-20.35	1.41	-6.15
2.0	3.97	8.59	-19.98	0.65	-13.27	-29.48	0.53	-16.3	--	--	0.00

Table 7.6 Threat assessment – red light violation – different deceleration capacities

The distinct deceleration capacities do not have any effect for -8 m/s² and -4 m/s² for the first three points in time. The results of the first three threat assessments are identical and no warning was issued. However, for the -2 m/s² there is a slight difference already 20.35 m before the stop line and the threshold for sending out the safety warning is exceeded for the first time at time point 1.0 s. The reason for this is that the changed deceleration capacity influences the prediction only when the needed deceleration exceeds -2 m/s². By setting the threshold for a safety warning to -2.5 m/s² and for the critical to -4.0 m/s², the following colored results are achieved (Table 7.6).

Completing the red-light scenario, it needs to be checked whether there are any false alarms while approaching a red light. These tests were also conducted with three different deceleration rates, as before. Table 7.7 presents the results of the threat assessment. All three predicted trajectories are rather identical and do not trigger a warning message. Slight differences are in the prediction with -2 m/s^2 in the second and fourth row.

point in time [s]	**d2RP_t0 [m]**	**v_t0 [m/s]**	**- 8 m/s^2**			**- 4 m/s^2**			**- 2 m/s^2**		
			d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]
0.0	22.79	8.56	2.12	5	-1.71	2.12	5	-1.71	2.12	5	-1.71
0.6	16.81	7.84	2.16	4	-1.96	2.16	4	-1.96	0.36	5	-1.57
1.0	14.50	6.96	2.10	4	-1.74	2.10	4	-1.74	2.10	4	-1.74
1.6	9.55	5.53	2.14	3	-1.84	2.14	3	-1.84	0.65	5	-1.11
2.0	9.06	4.59	2.10	3.5	-1.31	2.10	3.5	-1.31	2.10	3.5	-1.31
2.6	6.14	3.16	2.10	3	-1.05	2.10	3	-1.05	2.10	3	-1.05
3.0	5.54	2.21	2.10	3.5	-0.63	2.10	3.5	-0.63	2.10	3.5	-0.63
3.6	5.15	1.08	2.14	5	-0.22	2.14	5	-0.22	2.14	5	-0.22
1.0	4.24	0.68	2.19	5	-0.14	2.19	5	-0.14	2.19	5	-0.14
1.6	2.98	0.00	-- vehicle stopped --								

Table 7.7 Threat assessment – stopping at red light – different deceleration capacities

In combination with the experience for the test “Violating the Red Light”, the best parameter set for the implemented IRIS-System is a deceleration capacity of -2 m/s^2 for the prediction and thresholds of -2.5 m/s^2 for the safety warning and -4.0 m/s^2 for the critical warning for the threat assessment. These parameters are checked again in the scenario “Unprotected Left Turn”.

Unprotected Left Turn

The second scenario to be tested is the “Unprotected Left Turn”. The left turning driver has to pay attention to oncoming crossing vehicles. Three test runs with different deceleration capacities were conducted to analyze the performance of the threat assessment and to verify the identified parameter set. Table 7.8 presents the result of the threat assessment in the case the two vehicles collide. With all three deceleration capacities, the threat assessment triggers identical warning messages at the same point in time before the RP, with only one critical warning in the case of -2.0 m/s^2 at time point 24.6.

point in time [s]	**d2RP_t0 [m]**	**v_t0 [m/s]**	**- 8 m/s^2**			**- 4 m/s^2**			**- 2 m/s^2**		
			d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]
0.0	25.11	10.13	2.10	4.5	-2.25	2.10	4.5	-2.25	-1.62	4.2	-2.41
0.6	18.58	9.92	2.15	3.5	-2.83	2.15	3.5	-2.83	-8.27	2.51	-3.96
1.0	15.28	9.85	2.16	3	-3.28	2.16	3	-3.28	-15.22	1.93	-5.09
1.6	8.92	9.81	2.14	1.5	-6.54	-3.11	1.23	-7.97	-27.38	1.01	-9.67
2.0	5.13	10.18	-2.65	0.71	-14.32	-27.77	0.57	-17.7	-36.77	0.53	-19.09

Table 7.8 Threat assessment – conflict at unprotected left turn – different deceleration capacities

Table 7.9 shows the result in the case the left turning vehicle slows down to give the oncoming vehicle right-of-way. The prediction and thus the threat assessment for the deceleration capacities of 8.0 m/s^2 and -4.0 m/s^2 are identical. In the case of -2.0 m/s^2, a safety warning message was triggered 8.45 m before the conflict point. Considering these facts, the best choice for the parameters is a maximum deceleration capacity of -4.0 m/s^2 and thresholds for triggering the messages of -2.5 m/s^2 for the safety warning and -4.0 m/s^2 for the critical warning.

point in time [s]	**d2RP_t0 [m]**	**v_t0 [m/s]**	**- 8 m/s^2**			**- 4 m/s^2**			**- 2 m/s^2**		
			d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]	d2RP_t10 [m]	t2RP [sec]	req. acc. [m/s^2]
0.0	18.90	6.44	2.13	5	-1.29	2.13	5	-1.29	2.13	5	-1.29
0.6	14.10	4.99	2.12	5	-1.00	2.12	5	-1.00	2.12	5	-1.00
1.0	12.00	4.53	2.11	4.5	-1.01	2.11	4.5	-1.01	2.11	4.5	-1.01
1.6	9.67	5.19	2.11	3	-1.73	2.11	3	-1.73	2.11	3	-1.73
2.0	8.45	6.01	2.12	2.5	-2.4	2.12	2.5	-2.4	-2.79	2.14	-2.81
2.6	4.19	7.26	2.13	5	-1.29	2.13	5	-1.29	2.13	5	-1.29

Table 7.9 Threat assessment – slowing down at unprotected left turn – different deceleration capacities

The last test in this section is to prove whether there are false alarms during a left turn while there is no other vehicle oncoming. Therefore, an undisturbed left turn should be possible. The tests for the prediction of the trajectories in these scenarios described at page 124 suggest the assumption that there might be warnings triggered because the predicted trajectory make the vehicle slow down before the resistance point even in cases without any oncoming vehicle. The tests with no oncoming vehicle lead to the same results, as the vehicle might slow down properly in front of the fixed resistance point as presented in Table 7.9. That means that the IRIS-System and its threat assessment can be adjusted to reduce the occurrence of false alarms. This way the system can compensate shortcomings of the prediction through an appropriate parameterization of the threat assessment. For the proof of concept this might be sufficient, but not for a system running permanently at a real intersection. For that purpose, the concept of two conflicting reference tracks need to be refined first and the prediction of the trajectories need to achieve better results and get closer to the real trajectories.

Conclusion

The threat assessment was tested for the scenarios ‘Violating and Stopping at the Red Light’ and ‘Unprotected Left Turn’. The assessment is applied to the predicted trajectory. Therefore, the threat assessment strongly depends on the result of the trajectory prediction. Some minor shortcomings in the prediction can be smoothed out by setting appropriate thresholds for issuing a warning and by adjusting the deceleration capabilities of the vehicle. The later parameter influences more the prediction, but indirectly also the results of the threat assessment. Unfortunately, one major drawback of the IRIS-System is the prediction in the case of two conflicting reference tracks. The prediction and therefore also the threat assessment is not really influenced by an oncoming vehicle. This is due to the prediction rules formulated at page 66. One of the rules states that the predictions of vehicles at different reference tracks are independent from each other to reduce computation complexity. This is a correct decision, but in the case of two conflicting RTs an exception should be allowed and the concept needs to be adjusted in that typical case. Nevertheless, considering the results of the tests, the best choice of parameters is a maximum deceleration capacity with a value of -4.0 m/s^2. The thresholds for triggering the warning messages should be set to -2.5 m/s^2 for the safety warning and -4.0 m/s^2 for the critical warning. Taking these results into account the hypothesis, whether it is possible to design a system, which can monitor and asses the driving maneuvers at an urban intersection can be verified.

The remaining is to answer the question, whether it is possible to proof the system design at a real urban intersection? With the elaborated settings, the IRIS-System is ready to be tested at the real intersection to answer the open question. The results of these tests are presented in the following paragraph.

7.2 Testing at the Real Intersection

7.2.1 Installations at the Test Site and Test Vehicles

Equipped Intersection

The field tests in Dortmund were conducted in August 2009 and February 2010 and are based on the experiences gathered beforehand in the laboratory, as reported in the previous chapters. To test the technology and the integration of all necessary components to run the IRIS-System successfully, the tests were conducted at a public intersection with regular traffic flow according to [SCHENDZIELORZ ET AL., 2010].

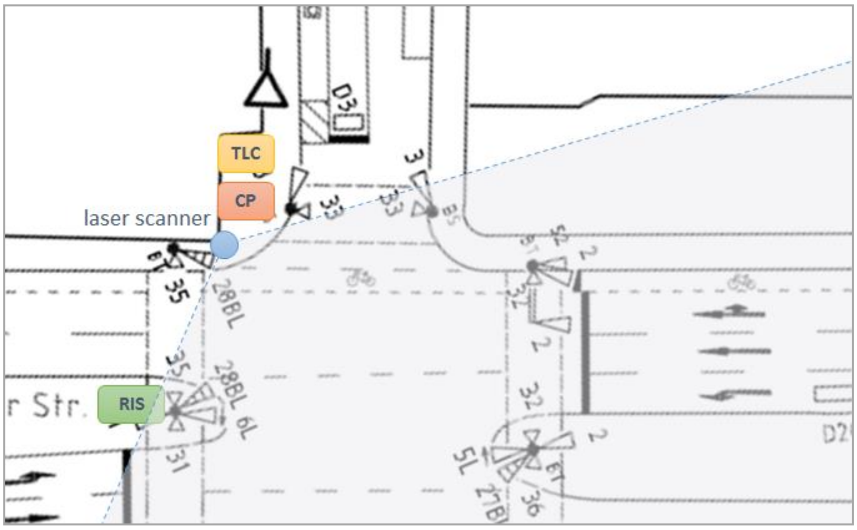


Figure 7.40 Blue print of the intersection and the roadside installations

The blue print of the intersection (Figure 7.40) depicts the additional equipment installed for the testing. The traffic light controller (TLC) is located in a cabinet at the upper left corner of the intersection in the picture. Close to the cabinet, an additional computer includes a control panel (CP) for controlling the IRIS-System. It is linked to the TLC as well to the ITS roadside station (IRS). At the same corner, the laser scanner is installed at the ground level surveying bicycles and pedestrians approaching parallel to the main street. The traffic lights pole in the left corner of Figure 7.40 on the main street holds a small cabinet, the IRS, which contains a computer hosting the IRIS-System.

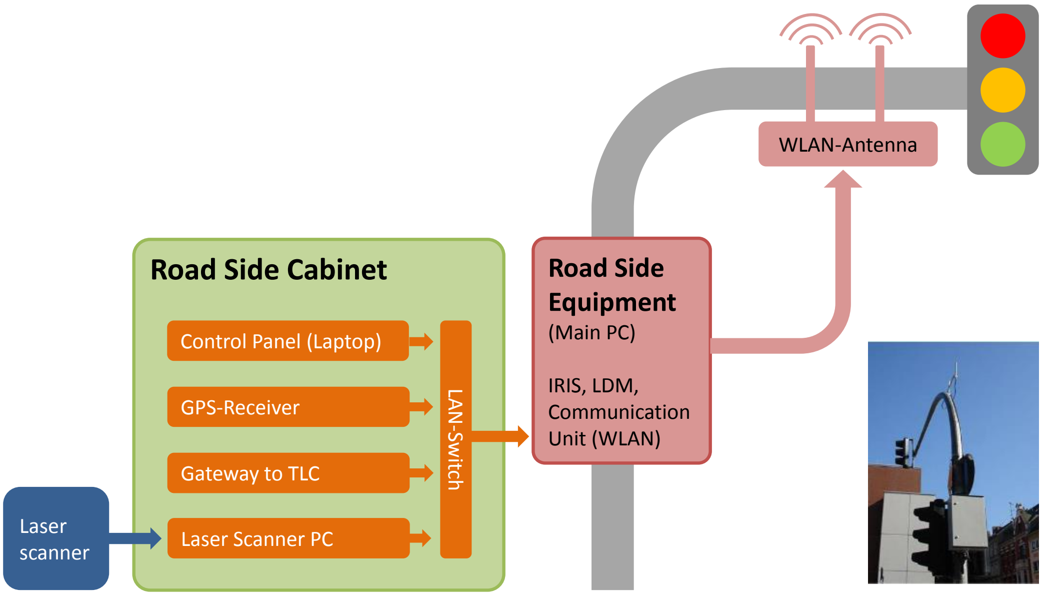


Figure 7.41 Installation schema at the intersection of the hardware and of the real IRS in the right lower corner of the picture

Figure 7.41 depicts the hardware installed at the different locations. The control panel is located in the roadside cabinet. The cabinet comprises also a GPS receiver to get the GPS time. All the different computers at the roadside are synchronized to this time. This ensures that the time at the roadside and the time in the vehicles, which get their time also from GPS receivers, are the same. Therefore, the GPS time is the reference time for all system components. This is completely in line with Gruyer et al. [2001]. He states that the first step of data combination consists of synchronizing the information on the same time scale. Furthermore, a gateway to the traffic light controller is essential to receive information about the traffic light control at the intersection.

The laser scanner provides proprietary raw data - representing raw measurement results per scan. This data is sent to the laser scanner processing unit in the road side cabinet. The input from the static map, which is part of the Local Dynamic Map (LDM), describes the general road geometry. This map information is superposed with raw data and so the laser scanner module distinguishes between scan data, representing background objects and scan data at foreground objects such as bicycles. According to Kutila et al. [2007a], the scanner provides data on the relative bicycle position and speed of the bicycle in a frequency of 12.5 Hz.

All the data and information are transmitted by wire to the roadside equipment containing the main computer. This PC hosts the actual intelligence of the system; the components of IRIS, the LDM and the communication unit. Furthermore, the necessary antennas are mounted to the top of the same pole to enable a wide communication range. A communication range of more than 500 m on the main road (Hamburger Straße) could be achieved. On the side road, only a range of about 300 m was possible because the buildings are closer to each other and trees are obstructing the communication line of site. The communication unit executes the data exchange with the vehicles over IEEE 802.11p using the proprietary VANET routing software of the SAFESPOT project. The other entire roadside-based computers are connected via Ethernet.

Equipped Vehicles

For testing the IRIS-System three different vehicles (Figure 7.42) were used; the Continental Automotive test vehicle was a BMW 5 series, the test vehicle of Technical University of Chemnitz was the concept vehicle “Carai” a VW Touran and the test vehicle of Daimler was a SMART.

Figure 7.42 Test Vehicles: BMW 5, VW Touran and Daimler SMART [Schendzielorz et al., 2010]

Figure 7.43 depicts the onboard vehicular communication system equipment. The equipment was identical for the CVIS and SAFESPOT project. As different communication technologies were used in the projects, the onboard equipment contains more than one radio transmitter. The mobile router performs all networking operations and acts as the interface to the vehicle processors and sensor. The mobile router contains a special-purpose card that integrates sensors and resolves time-critical tasks such as the real-time acquisition of location and time and synchronization [PAPADIMITRATOS ET AL., 2009].

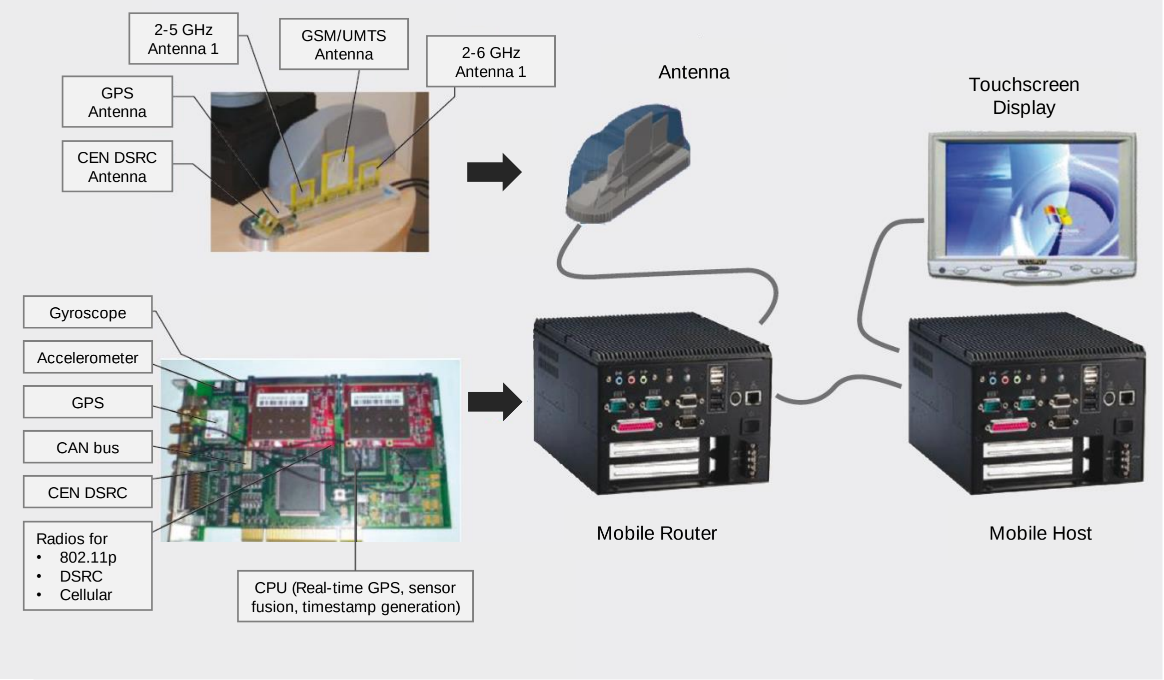


Figure 7.43 Onboard vehicular communication system equipment referring to PAPADIMITRATOS ET AL. [2009]

With some minor differences such as the antenna and no gyroscope, this communication equipment was also installed at the roadside. Therefore, from a communication point of view, the IRS can be regarded as a stopped vehicle at the intersection. Finally, a human machine interface to display the warnings to the drivers was provided by using a touch screen display. Figure 7.44 shows an example of the HMI of the test vehicle of Continental.

Figure 7.44 Continental HMI for the scenario pedestrian or bicyclist on the right side [PU ET AL., 2010]

Pre-testing the Complete System

The test at the real intersection started with some pre-tests before the testing started. The pre-testing of the communication facility at the real test side showed that there is a certain time delay t^d from the point in time when the vehicle's position is calculated by the onboard systems to the moment the information reaches the IME-process in the IRS. It turned out that this delay could be up to 1 s. This is quite critical, as the movement of a vehicle driving at 50 km/h is 13.88 m in 1 s. Therefore, this occurrence needs to be counterbalanced. If there is any delay observed and the speed of the vehicle is larger than 0.1 m/s, this phenomenon is compensated by linearly approximating the position and the speed of the vehicle for the length of the delay. The measured speed transmitted via the VANET at the time $t = 0$ and $t = -1$, which is the second last measured value that allows for computing the acceleration $a_{ik,0}$ of the vehicle i assigned to the reference track k at the beginning of the prediction $t = 0$. The acceleration $a_{ik,-1}$ is received accordingly. Equation (7.9) estimates the additional acceleration Δa^d because of the delay with the difference in time of the last and second last received measurement t_{ik}^{Δ}.

$$\Delta a_{ik}^{d} = (a_{ik,0} - a_{ik,-1}) \cdot \frac{t^d}{t_{ik}^{\Delta}} \tag{7.9}$$

The speed of the vehicle is therefore adjusted by adding the additional acceleration component a_{ik}^{d} to the acceleration $a_{ik,0}$ (7.10):

$$\Delta v_{ik}^{d} = \left(a_{ik,0} + \Delta a_{ik}^{d}\right) \cdot t^d \tag{7.10}$$

Thus, the distance the vehicle has travelled during the delay t^d can be approximated by:

$$\Delta d_{ik}^{d} = 0.5\left(a_{ik,0} + \Delta a_{ik}^{d}\right) \cdot (t^d)^2 + v_{ik,0} \cdot t^d \tag{7.11}$$

According to this information, an update moving resistance point reflecting the status of the vehicle at $t = 0$ is computed. For details on the resistance point and the computation of the attributes of the resistance point see paragraph 5.3.

After having figured out the problem of the delay and creating a workaround to solve it, the complete system including all components at the infrastructure and in the vehicles had to prove its performance in 124 test runs according to the following concept.

7.2.2 Test Scenarios and Concept of the Tests

The following scenarios were tested in Dortmund: red light violation, right turning while avoiding cyclists, right turning while avoiding pedestrians and unprotected left turning with regard for oncoming vehicles.

Red-light violation: The first aim is to detect imminent red-light violation as early as possible to warn all the concerned road-users. The second is to warn a driver who is at risk of violating the red light. As the tests are taking place at a real intersection, no real violation of a red light was possible in order not to endanger any other road users. Therefore, a virtual stop line was defined in the LDM and marked on the side of the road, as Figure 7.45 shows.

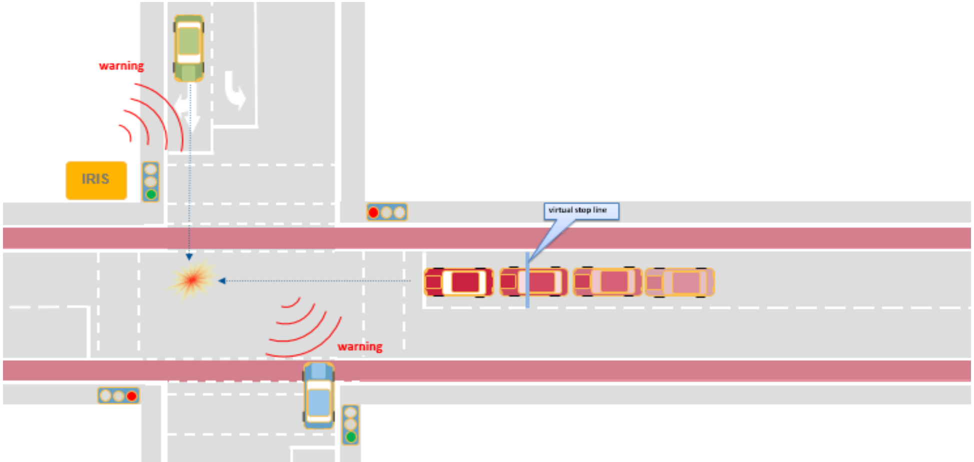


Figure 7.45 Test scenario – red light violation – warning (broadcast)

Before these two tests, it was verified whether the system stays quiet if the vehicle passes at green and if the vehicle stops correctly at the red light. Therefore, these four test cases dealt with the red-light violation:

- *Test Case 1 – red-light violation - green*
- *Test Case 2 – red-light violation - red stop*
- *Test Case 3 – red-light violation - warning (unicast)*
- *Test Case 4 – red-light violation - warning (broadcast)*

Test Case 5 - right turn – cyclist: While turning right, the driver must pay attention to cyclists approaching the intersection parallel to him and crossing the road he wants to enter. The aim is to warn the driver if there is the risk of a collision with a cyclist (Figure 7.46).

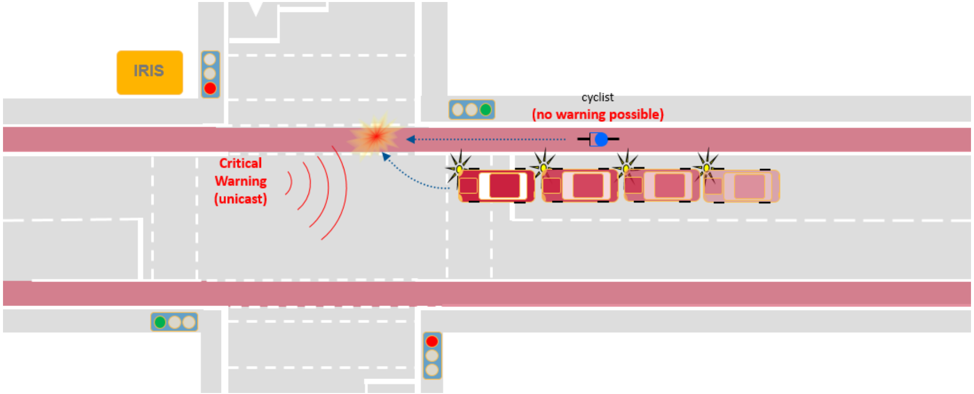


Figure 7.46 Test scenario – right turning avoiding cyclists

Test Case 6 - right turn – pedestrian: While turning right, the driver has to pay attention to pedestrians crossing the road in which the driver wants to enter. The aim is to warn the driver if there is the risk of a collision with a pedestrian. Figure 7.47 depicts this test scenario.

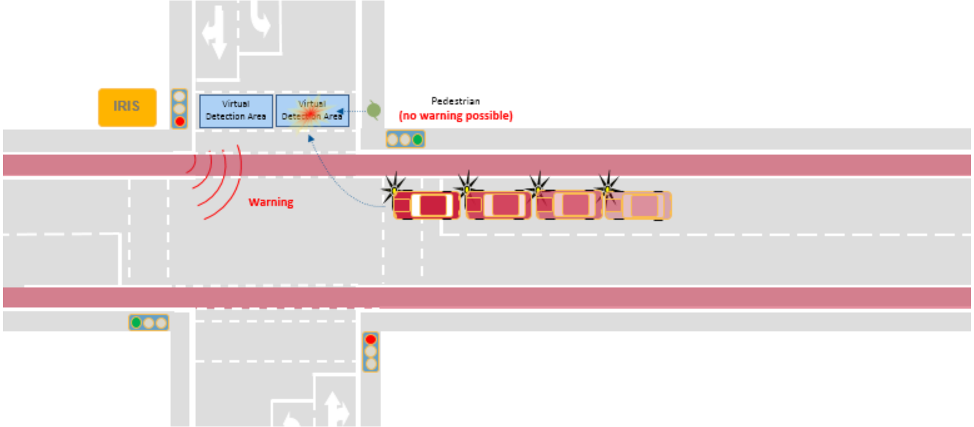


Figure 7.47 Test scenario – right turning avoiding pedestrians

Test Case 7 - left turning – vehicle: During a left turn, the driver needs to pay attention to oncoming vehicles Figure 7.48. The IRIS-System assists the driver especially in the case of other vehicles blocking the view when there are two lanes going straight.

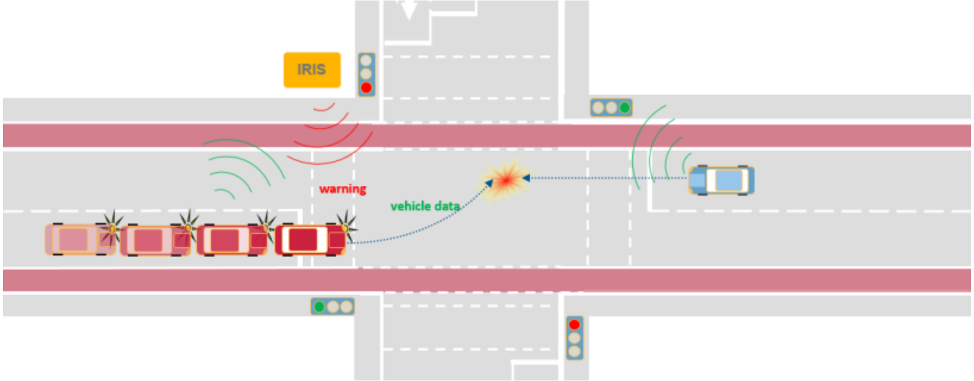
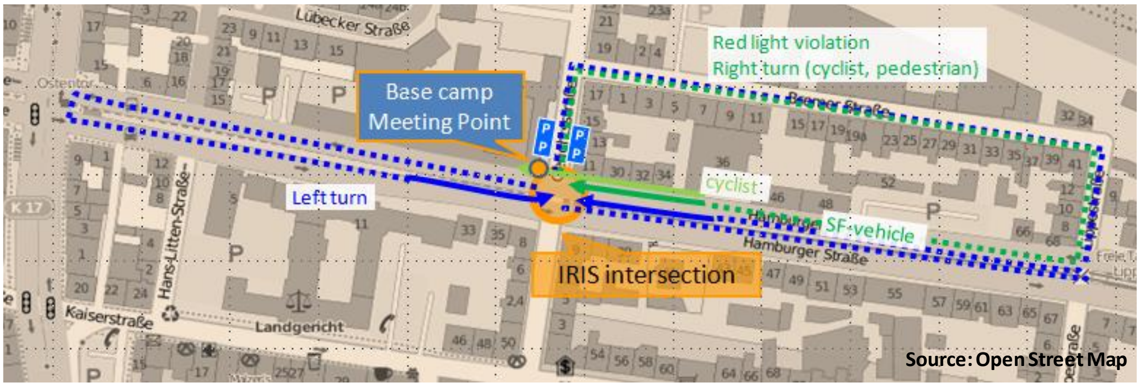


Figure 7.48 Test scenario – unprotected left turn

To run these defined test scenarios, the three test vehicles (SAFESPOT/SF-vehicles) had to drive along a predefined course around the intersection. To coordinate the test activities and the actors, a meeting point was established next to the traffic light controller. The entire test personal met before and after tests. During the tests, walky-talkies ensured the communication between test site leader and drivers. Figure 7.49 illustrates the street network surrounding the IRIS intersection including the meeting point and the routes for the different test scenarios.



Source: Open Street Map

Figure 7.49 General map of IRIS intersection including routes for the tests [SCHENDZIELORZ ET AL., 2010]

Before running the test, the test site leader gave a general introduction to the current scenario (definition of the focus of test, adjustment of systems and procedure for actors). Each test run started with the actors waiting at pre-defined positions and starting the onboard systems and the system installed in the infrastructure. The test site leader gave a “GO” and the drivers followed the predefined route including intended behavior (e.g. red-light violation). The co-driver noted the correct presentation of the message and reported the reception of the message in the vehicle via walky-talky.

In order to be able to compare the tests and to exclude the bias because of special events and to avoid the endangering of other road users the test took place during the same general conditions, which are:

- Daylight, no precipitation
- Normal road surface friction
- No other hindering vehicles in front or behind the probe vehicle
- Vehicles keep their defined lane and do not overtake other vehicles
- Vehicles are driven by professional drivers with co-drivers

Before starting the test ride, the test conditions, such as traffic and weather conditions, kind of vehicle used, desired speed while approaching the intersection and settings of the IRIS-System, were noted. Because of the requested technical leanness of the system, unfortunately a vehicle internal recording of the point in time when the message was displayed to the driver was not possible. Therefore, the acquisition of the warning message in the vehicle is measured by direct voice communication between the co-driver and test site staff. The co-driver notes the correct presentation of the message and reports the reception of the message in the vehicle via walky-talky. The test site staff that is also equipped with walkie-talkies observes the test vehicle approaching the intersections and determines the distance to the stop line when they hear the co-driver’s announcement. Traffic cones are placed parallel to the road every 10 m to identify the distance of message reception from the stop line. This approach assumes that the time to report the message (“Message received”) needs as much time or even more to initiate a braking maneuver.

Figure 7.50 Traffic cones at the roadside for marking the distance during the tests

As the tests took place in an open driving environment and to avoid any injuries of the test personal or any other road user nearby it was not possible to provoke critical or even dangerous situations. For that reason, the drivers were instructed to brake or evade before the actual situation, if they receive the warning too late or no warning. Based on the manually recorded point in time when a warning message was received in the vehicle, the possible reduction of the speed up to the critical point can be computed by applying smooth braking with 2 m/s^2, normal braking with 4 m/s^2 and emergency braking with 8 m/s^2 in a theoretical way. An advantage of this procedure is that the manual recording includes the human reactions time automatically. Doing so, the ability to stop in front of the critical point by applying smooth, normal and emergency braking behavior can be compared.

Reduction of Speed	According Energy Reduction	Impact Reduction Class
[100%[	[100%[	Accident Avoidance
[100%, 87%[	[100%, 50%[	High Mitigation
[87%, 71%[	[75%, 50%[	Mitigation
[71%, 0%]	[50%, 0%]	Low Mitigation

Table 7.10 Impact reduction class and respective speed reduction

As kinetic energy plays an important role in traffic safety, the possible reductions of the speed were assigned to categories expressing the theoretically possible reduction of kinetic energy of the violating vehicle. The ratio of kinetic energy to speed is $E \sim v^2$, meaning that if speed if reduced by 50%, kinetic energy is reduced by 75%. If 100% of the kinetic energy is transformed into deceleration energy, the accident is avoided. High impact mitigation is defined as when the driver can transform at least 75% of the kinetic energy. Normal mitigation occurs when about 50% of the kinetic energy is transformed. Everything less than 50% transformation can lead to accidents which are not well mitigated. Table 7.10 condenses this concept and assigns the according reduction of the impact to each speed and energy reduction class.

7.2.3 Test Results at the Real Intersection

Altogether 124 test runs were conducted. In 55% (68 runs) of all the tests, the system worked without any disturbances. In 39 tests, at least one problem occurred. In most of the cases, the problem was in displaying the message in the vehicle. Therefore, the LDM of the vehicles was checked in real-time whether the message was received or not. A workaround was set up to signal the reception of the message in the LDM of vehicle. It was not possible to discover the reason for these shortcomings while testing, but possible reasons might be

- an accidental misuse of the HMI-message structure,
- all components were prototypes, this fact occasionally leads to instabilities,
- overruns of internal memories because of logging mechanisms and
- instabilities in computing the heading of the vehicles.

Therefore, it should be noted that if a shortcoming in the vehicle HMI is reported, the reason for that does not have to be in the HMI itself. In fact, another component could be the reason for that, too. Due to the complexity of the system and time restraints during test activities, this could not be resolved within time. Looking at the IRIS-System individually, it worked properly in 114 test runs and only in 10 runs there were some shortcomings such as the loss of connection to the traffic light controller or a sudden breakdown of the application. For a prototyped software, this is assumed to be very satisfying.

Figure 7.51 shows the report protocol for the tests on the example of the red-light violation test. The tested scenario is named in the header of the protocol and the route, which the vehicles have to take, is reported, too. Each test has a unique identifier, the speed of the vehicle is logged and the status of the traffic light. Furthermore, a column for remarks offers space to take notes of important incidents during the test. In the last column, the distance before the stop line is reported. The possible reduction of speed and therefore reduction of kinetic energy is computed automatically by the spreadsheet.

Test Case 3	Basic Settings				Speed Reduction (2m/s²)	Speed Reduction (4m/s²)	Speed Reduction (8m/s²)
run_id	actor	role	speed	traffic light			
013_01	vehicle	violator	50	red	-	-	
013_02	vehicle	violator	50	red	-	-	-
013_03	vehicle	violator	50	red	⇩ 4.15%	⇩ 8.29%	⇘ 16.59%
013_04	vehicle	violator	50	red	⇘ 24.88%	⇘ 49.77%	⇧ 99.53%
013_05	vehicle	violator	50	red	-	-	-
013_06	vehicle	violator	50	red	⇘ 29.03%	⇗ 58.06%	⇧ 100.00%
013_07	vehicle	violator	50	red	⇘ 35.25%	⇗ 70.50%	⇧ 100.00%
013_08	vehicle	violator	50	red	⇘ 41.47%	⇧ 82.94%	⇧ 100.00%
013_09	vehicle	violator	50	red	-	-	-
013_10	vehicle	violator	50	red	-	-	-
013_11	vehicle	violator	50	red	⇘ 29.03%	⇗ 58.06%	⇧ 100.00%
013_12	vehicle	violator	50	red	⇘ 20.74%	⇘ 41.47%	⇧ 82.94%
013_13	vehicle	violator	30	red	-	-	-
013_14	vehicle	violator	30	red	-	-	-
013_15	vehicle	violator	30	red	⇘ 28.80%	⇘ 57.60%	⇧ 100.00%
013_16	vehicle	violator	30	red	⇘ 28.80%	⇘ 57.60%	⇧ 100.00%
013_17	vehicle	violator	40	red	⇘ 35.64%	⇗ 71.28%	⇧ 100.00%
013_18	vehicle	violator	40	red	⇘ 35.64%	⇗ 71.28%	⇧ 100.00%
013_19	vehicle	violator	40	red	⇘ 32.40%	⇗ 64.80%	⇧ 100.00%
013_20	vehicle	violator	60	red	⇘ 46.08%	⇧ 92.16%	⇧ 100.00%
013_21	vehicle	violator	60	red	⇘ 44.64%	⇧ 89.28%	⇧ 100.00%

Figure 7.51 Example for the reporting of the test results at the real intersection

Altogether 68 test runs could be evaluated and the possible reduction of the kinetic energy computed. As mentioned before, it was distinguished between smooth braking with 2 m/s², normal braking (4 m/s²) and emergency braking (8 m/s²). Table 7.11 summarizes the results for the different tests. It reports the technical success rate and the reduction of kinetic energy applying a normal braking behavior. In the test cases 1, 2 and 4 no braking was necessary as it was only important whether the system generates a warning message or not. The table reports the total number of the tests, the number of test of which all the components of the system work perfectly and the number of the test where at least everything worked fine up to the IRIS-System, so that IRIS could run the threat assessment. An impact reduction could be determined as soon as the message was received in the LDM of the vehicle. Therefore, the number of tests in which the IRIS-System run successfully and the number of tests for which the impact reduction was computed can differ. The reason for this fact are problems in interpretation of the message onboard the vehicle. The detailed results and a complete summary can be found in the Annex of the document.

Test Scenario	**Number of Tests**	**Complete Test OK**	**IRIS OK**	**Impact Reduction at 4 m/s²**			
				Accident Avoidance	High Mitigation	Mitigation	Accident (Low Mitigation)
Test Case 1 - red light violation - green	6	6	6	--	--	--	--
Test Case 2 - red light violation - red stop	6	5	6	--	--	--	--
Test Case 3 - red light violation - warning (unicast)	38	15	33	0	4	8	15
Test Case 4 - red light violation - warning (broadcast)	23	6	21	--	--	--	--
Test Case 5 - right turn - cyclist	35	20	32	0	1	11	9
Test Case 6 - right turn - pedestrian	12	12	12	5	1	3	3
Test Case 7 - left turning - vehicle	4	4	4	0	4	0	0
Total Number	124	68	114	5	10	22	27

Table 7.11 Summary of test results for the impact reduction of 4 m/s²

Figure 7.52 summarizes the total numbers and Figure 7.53 the percentage of the results of test cases applying different braking behavior. Only in 2% of the tests (1 test) smooth braking would lead to a complete avoidance of the accident. In 8% of the test cases (5 tests), normal braking behavior could prevent an accident and an avoidance rate of 76% (49 tests) could be reached by braking very hard. Only in 42% of all the tests (27 tests) less than half of the kinetic energy could be reduced by braking normal and in 3% (2 tests) by braking hard. It should be noted that not only braking prevents the accident, but also the avoidance of critical situations by proper steering maneuvers. This possibility was not investigated during the test period. Further investigation is needed in the field of driver behavior and human factors but also in the fine-tuning of the complete cooperative system and in particular the IRIS-System.

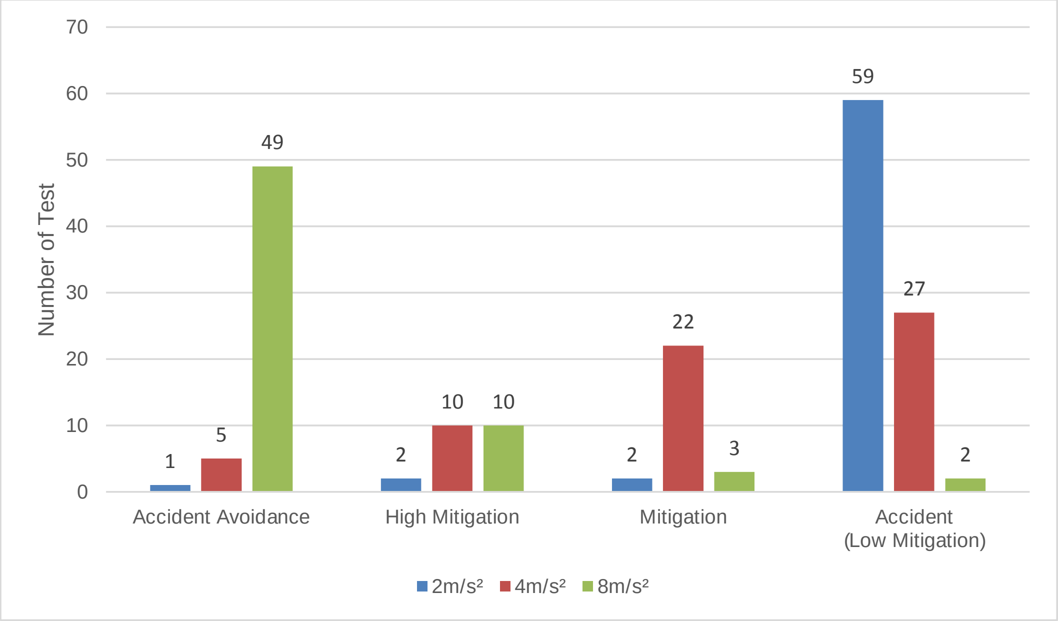


Figure 7.52 Results of the IRIS field test – impact reduction (total numbers)

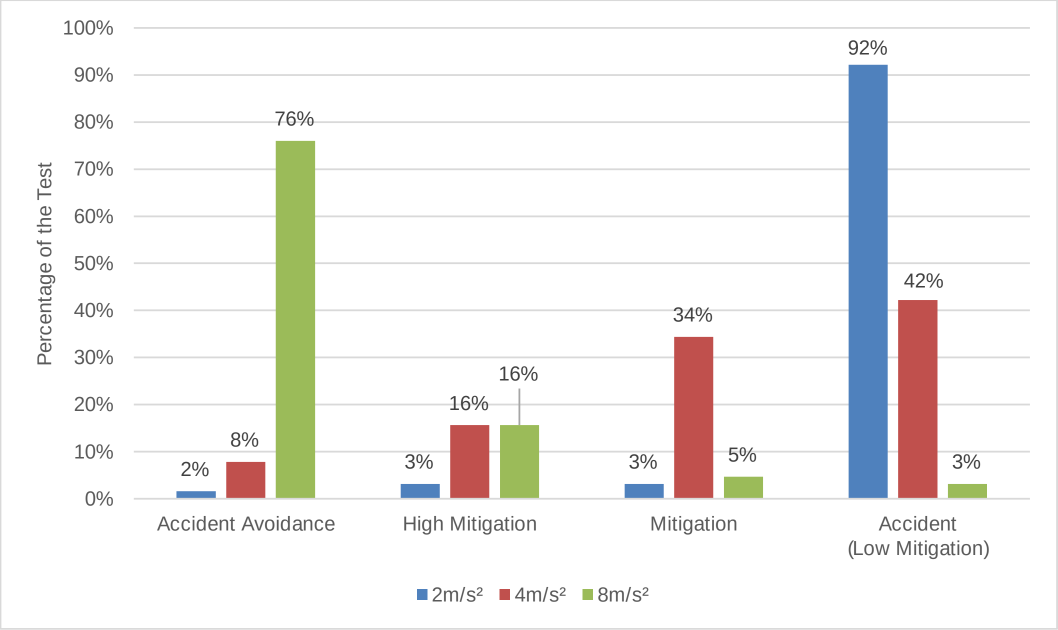


Figure 7.53 Results of the IRIS field test – impact reduction (percentage)

Conclusion

The Intelligent Cooperative Intersection Safety System – IRIS has been tested successfully at a real intersection in the City of Dortmund. The developed components running in the IRS at the traffic light controller of an urban intersection were able to cope with the amount of data coming from the vehicles, infrastructural detectors and the traffic light controller. In 92% of the tests, the IRIS-System could interpret the evolving situation at the intersection correctly. The technical testing at the intersections showed a good inter-operability between infrastructure-based components and the components of the SAFESPOT system running in the vehicles. Nevertheless, in 8% of the tests in Dortmund, technical shortcomings such as the lost connection to the traffic light controller prevented the correct interpretation. Therefore, further effort is required to make the whole system more reliable.

7.3 Review of the IRIS-System

The laboratory and the tests at the real intersection showed that there is a great potential of the IRIS-System to deliver a contribution for safe urban intersections. Furthermore, the hypothesis, whether it is possible to proof the system design at a real urban intersection could be verified. However, from proofing a concept to deploying a system some open issues and questions need to be answered. The IRIS-System and the necessary preconditions are not yet ready for a deployment with blanket coverage.

7.3.1 Issues on the Concept

The intensive tests in the laboratory and on the real test side showed good results and the concept itself could be proofed. Nevertheless, during the tests some points came up which are valuable to consider as leverage points for improving the IRIS-System.

The estimation of maneuvers and the prediction of the vehicles are based on reference tracks. These tracks define the most likely path a vehicle might follow passing an intersection. For proofing IRIS at the intersection in Dortmund the reference tracks were manually designed. However, to come up with more suitable reference tracks traffic observations should be done beforehand. Additionally, the IRIS-System should be extended by a kind of self-learning process for constructing the RTs based on the data received from the vehicles passing by. But still the prediction is based on the RTs and the IRIS-System cannot cope with vehicles leaving the RTs while passing the intersection in a misguided way. Though, there is no need for IRIS to deal with that kind of situations. IRIS is designed for assisting the driver in potential unclear situations and not preventing him for misguided behavior.

The prediction of the trajectories strongly depends on the typical speed assigned to the reference tracks and on the required speed assigned to the resistant points. Therefore, it is recommended to conduct traffic observations at the intersection where IRIS is planned to be installed for adjusting these parameters. For instance, the driver choses the speed while turning right not only on the surrounding traffic but also based on the topographic of the intersection. For proofing the concept of IRIS these values were estimated but not measured. Also, the predicted speed sometimes differs from the actual speed of the vehicle. To overcome this firstly the typical speed and required speed should be verified by speed observations before installing the system or implementing a kind of self-learning procedure analyzing the speed values the vehicle have while passing the intersection. Secondly, the speed sent by the vehicles or detected by any other sensor could be included as a correction factor in the prediction of the trajectories. In addition to that, the time the prediction procedure takes to be executed should be included as the vehicle might run a certain small distance during this processing time.

Furthermore, the type of vehicle and the driver were not considered yet. Different vehicles have different acceleration capabilities; a sports car accelerates much faster than a truck. This information could be sent to IRIS by the vehicle themselves or detection devices such as cameras or laser scanners could be enabled to provide data on the vehicle type. Also, the driver themselves play a major role as they have different driving behavior while approaching an intersection, especially the dilemma zone topic needs to be considered in future projects.

In the future Object Refinement cannot be neglected anymore. Remember the objective of the Object Refinement is to clarify whether different data sources provide information on the same object or not. And if the object, e.g. a vehicle, provides data itself, it needs to be figured out to which object this information needs to be assigned to. The Object Refinement clarifies that there is an object of interest and then consolidates the attributes of that object, such as position, speed or acceleration. For a further improvement of IRIS this task should be tackled.

In addition, there is also room for improvement of the estimation of the maneuvers. More information should be take into account for the estimation, e.g. the speed of the approaching vehicle, turning rates at the intersection or, the type of lane (separate turning lane or mixed lane). Using Bayesian Networks for combining the additional information and improve the estimation of the maneuvers could be an appropriate approach.

The unprotected left turn at an intersection still has some drawbacks. The prediction and therefore also the threat assessment are not influenced in an appropriate way by an oncoming vehicle. This is because of the prediction rule, that the model does not consider cross-correlations of vehicles on different reference tracks; i.e. the movements of two different vehicles on two different reference tracks are independent from each other. The reason for this restriction is to reduce algorithmic complexity. This is a correct decision, but in the case of two conflicting RTs an exception should be allowed and the concept needs to be adjusted in that typical case.

Furthermore, the prediction of the residual probability of the traffic light can be improved by combining the IRIS-System with a system providing predictions on traffic light signals as well that the vehicle is treated like a point and that the dimensions of the vehicle are included by setting the length of the vehicle to constant four meters leave space for improving the IRIS-System.

Beside the issues on the concept, there are also aspects on the deployment of a system such as IRIS that need to be mentioned as well. Assuming the concept is further elaborated and passed the final tests the following in the next paragraph should answered, too.

7.3.2 Issues on the Deployment

The costs of the installed components were rather high for a single intersection. The used laser scanners were at the status of a prototype and not yet ready for mass production, which would lower the price of the single entity. The traffic controller had to be renewed to interface it properly and to extract the required information on the traffic light control. Furthermore, an IRS comprising a computer and a WLAN transmitter had to be mounted at the traffic light pole. In addition to the installation costs, were costs for preparation and maintenance on the pay role. The most men power consumed the preparation of the additional content of the LDM, the reference tracks and the position of the stop lines. In case of a construction site or a reconstruction of the intersection the contented of the LDM needs to be updated as well. The mounted system must be robust against weather and any other treatment from outside to assure a continual function of the system. For preparing a single intersection during the field tests in the SAFESPOT project these efforts were manageable or did not play any role such as maintenance issues.

Another question that is still open to be answered: Who is paying for these costs? Is it the municipality who is asked to equip the intersections? Is it the owner of the vehicle? Is it the car manufacturer? Or is it a service provider or any combination of these stakeholders? Now, there is no proper business case. This is certainly because the customer does not feel immediately happy and satisfied having paid for this product or service. The customer only gets aware of the benefit of a safety assistance system of the kind of the IRIS-System in the rare moment of the avoidance of a serious crash. This is different for e.g. buying a new smartphone. Therefore, the situation is in some points like the introduction of the safety belt. This was forced by law and the car manufactures had to install this safety feature and the wearing of the belt needed to be enforced by the police. It is supposed that the government is in charge to foster the installation of these safety systems such as IRIS if there is a decision for deployment in a wide area. Furthermore, it is quite reasonable not to equip each intersection controlled by a traffic light, but to select accident-prone ones to safe costs and increase the benefit.

The legal issues bring also a huge potential for discussion: Who is responsible if the system fails? Is it the driver, the car manufacture, the service provider or the municipality? A municipality would never allow to install any device at the intersections for which the municipality is liable for in case of failure. There is a similar situation for the service provider. As the system is not only installed in the vehicle, the car manufacturer would also not seek for being responsible in case of a system failure. So, only the driver is left. That means that the IRIS-System needs to be configured and the information and warnings need to be presented to the driver in a way that he accepts the IRIS as an assistance system but not a system taking off the responsibility of the driver. Also in case of a missing warning or false warning the situation should not be worse compared to the situation without the system. IRIS is an add-on but not a substitute for a responsible driver. Otherwise, there is a small chance for this kind of system to come into being.

A look at standardization: The standardization activities are quite ahead. At the time of testing IRIS, a proprietary beacon signal message format was used, now there is the CAM as a first release of ETSI. The MAP message mainly developed by the SAE includes a similar concept to describe the intersection topology as used by IRIS. The LDM comprises the reference tracks and stop lines, this information can also be found in the MAP message, the reference tracks are named reference lanes instead. This topology information the MAP message offers is needed for the Personal Signal Assistant presented by BAUER [20.01.2015] and could also be used for the IRIS-System. So, IRIS can benefit from these first applications. An open issue is the format of the warning message. In the SAFESPOT project a proprietary format was used again. The task is to include the content of the IRIS warning message in the standardization process for the DENM. But, as IRIS is not the first and only intersection assistance system to be rolled out, this certainly will take a while. On top of these standardization issues comes the interface to the traffic light controller. This was also a proprietary solution during the project. But in the meantime, the standardization of the Signal, Phase and Timing (SPaT) Message made a huge progress. This message could also be provided to the IRIS-System as input for the prediction and threat assessment.

Finally, some thoughts on the way of communication: There is still a question of belief in either WLAN communication or mobile communication. Most of the big car manufactures foster the mobile communication as there is no additional equipment necessary at the road side and the coverage is wider and will come sooner as compared to the WLAN communication solution. The providers of road side equipment certainly foster the deployment of WLAN communication and decentralized solutions as there is a chance to sell hardware which is fully understandable and goes along with the IRIS concept.

This short look at deployment situation reveals some depending issues such as the look for the right business case, the legal questions or the standardization issue. Therefore, IRIS will certainly not be one of the basic applications being deployed in the first roll out phase of C-ITS. However, IRIS proved its concept and the great potential in the set of possible cooperative applications in the continuously evolving field of C-ITS.

8 Summary and Outlook

8.1 Summary

The presented thesis on monitoring and assessing driving maneuvers in order to improve the safety at cooperatively controlled urban intersections in the context of the IRIS-System started with an overview of the evolution of C-ITS. Only through the massive technical development in computation power and even more through the introduction of modern and capable communication technologies C-ITS have become a reachable vision for researchers and could be developed and tested. As an outcome of these research activities not only the gain on experience should be mentioned, but also the valuable input to the standardization organizations dealing with the new wireless data exchange among vehicles and the infrastructure equipment.

Furthermore, accident statistics show that it is worth thinking of intelligent solutions and systems to increase traffic safety in urban driving environments, such as IRIS. This need for assisting drivers at intersections is not new to researches. In 2013 the German police recorded 65,545 crashes of vehicles with another vehicle, which turned or crossed in the urban environment. There are two main categories of intersection safety systems: stand-alone and cooperative ones. The stand-alone systems independently collect information from their surrounding environment or having this information already integrated in their onboard navigation system in case of a vehicle system and draw appropriate conclusions. That means that only the infrastructure or only the vehicle is responsible for dealing with situations and for assisting the driver. Cooperative systems, on the other hand, exchange information and draw conclusions based on exchanged data. The Intelligent Cooperative Intersection Safety System – IRIS is a pretty good example for a cooperatively working system.

The IRIS-System is based on the wireless data exchange between vehicles and the infrastructure components. Based on the precise position information provided by the vehicles, the information on the control status of the traffic light controller, and a detailed digital map, the IRIS-System can reproduce and to predict the traffic situation at the intersection from a ‘bird’s eye view’. IRIS assesses the evolving situation and identifies safety critical situations at intersections by using this ‘bird’s eye view’. The result of the threat assessment leads to the decision whether an appropriate warning message needs to be transmitted to a vehicle in a critical situation.

The test in the laboratory showed that including the usage of the turning signal leads to better results in the estimation of the driving maneuver compared to only using the vehicles position information. The correct maneuver is not identified before the stop line. However, the assigned probability value to the correct maneuver is higher e.g. for a left turning vehicle; 0.2 without the turn signal and nearly 0.4 with the turn signal. Furthermore, the test showed that the system is rather sensitive to the positioning information. The geometric matching identified the lane on which the vehicle was driving on correctly, but only up to a standard deviation of 0.5 m. This underlines the importance of the prerequisite of a highly accurate positioning technique for the vehicles in safety applications. It might be an appropriate method to consider additional information using Bayesian Networks. Aspects such as the route advice of the on-board navigation system, the speed of the approaching vehicle, and the turning rates at the intersection might be included. This additional information would also lower the weight of the input value “turn signal”. The turn signal might also be not used by the driver. So, the human-in-the-loop is represented to a rather large extent at this state of the IRIS-System.

The prediction of the trajectories is based on reference tracks and the concept of resistance points. The resistance points are used to model the interdependencies between the vehicle and its driving environment. Each resistance point is located on at least one reference track and has its own required speed and driver awareness distance. The driver awareness distance is the distance at which the driver becomes aware of the resistance point. The required speed is the speed the vehicle is forced to go at during the prediction. The prediction of the movement of the vehicles showed the best results for a prediction time step of 500 ms and a positioning standard deviation of 0.5 m. The test also showed the importance or the dependency of the prediction on required speed. Observations of required speed at the intersection the IRIS-System is planned to be installed on are necessary to tune the system. The further the predicted waypoint is in the future, the larger the errors get, because the influence of the starting point of the trajectory, which is based on no predicted data from the vehicle, gets less and the influence of the required speed estimations becomes more. The unprotected left turn maneuver of the vehicle is hard to predict. It turned out that the system still has some difficulties to compute the correct required speed.

After the prediction of the trajectories the IRIS-System needs to assess the situation and decide whether there is the risk of a dangerous situation or not. For that task, the average required deceleration which is needed to get in line with the required speed is introduced. It is computed by the quotient of the difference of the required speed of the resistance point and the speed of the vehicle at the beginning of the trajectory and the time the vehicle needs to reach the resistance point based on the predicted trajectory. According to the value of the average required deceleration, a safety or a critical warning will be issued to the driver at risk. The tests in the laboratory showed that the deceleration capacity of the vehicles has a large influence on the issued warnings. The fact that the threat assessment is based on the predicted trajectories under the condition that the vehicles are assumed to brake very hard, will lead to very late warnings. Following the test results, the best choice of parameters is the maximum deceleration capacity of -4.0 m/s^2. The thresholds for triggering the warning messages should be set to -2.5 m/s^2 for the safety warning and -4.0 m/s^2 for the critical warning. Considering these results, the hypothesis, whether it is possible to design a system, that is able to monitor and asses the driving maneuvers at an urban intersection, can be verified.

Based on those parameters the IRIS-System has been tested at a real intersection. The developed components running in the IRS at the traffic light controller were able to cope with the amount of data coming from the vehicles, infrastructural detectors and the traffic light controller. In 92% of the tests, the IRIS-System could interpret the evolving situation at the intersection correctly. The technical testing at the intersections showed a good interoperability between infrastructure-based components and the components of the SAFESPOT system running in the vehicles. Nevertheless, in 8% of the tests in Dortmund, technical shortcomings, such as the lost connection to the traffic light controller, prevented the correct interpretation. Also, the hypothesis, whether it is possible to proof the system design at a real urban intersection could be verified successfully.

8.2 Outlook

The IRIS-System proved its capabilities in the laboratory and at the real test side. Nevertheless, the system is not yet ready for being implemented permanently at a real intersection. For that purpose, further effort is required to make the whole system more reliable by including further data sources, such as the motion detecting cameras mounted in many of today's urban intersections. This would require the data fusion algorithms to be enhanced and more research to be done, especially in the field of object refinement. In particular, in the case of information about the same object originating from different data sources requires the data to be fused and matched to the corrected object.

Furthermore, the estimation of maneuvers needs to make the algorithm able to identify the intention of the driver at an early state. This is not that easy to solve, as at the infrastructure-based components do not have as detailed data about yaw rate or steering rate as the vehicle itself. In case of the reference tracks, the IRIS-System could include a self-learning component which estimates the real path the vehicles take at the intersections based on the gathered positioning data. This would lead to better results in the prediction of the trajectories. Moreover, field operational tests in combination with virtual tests are required to gain more experience on how the system performs and how the driver accepts the system in the end. Overall, it could be shown that the concept of the IRIS-System is able to provide a valuable contribution towards making urban intersections safer places.

However, to achieve the vision of a safe urban intersection, some issues still need to be solved. Systems such as IRIS bring along legal questions. Who is responsible in case the system fails and a crash will happen - Is it the driver, the car manufacture or the municipality? Also, the investment costs are an impediment for systems based on the presence of a road side installed communication unit.

Nevertheless, the current activities in the field of C-ITS show that the automotive industry and the municipalities along with the infrastructure suppliers are starting to work together to solve these open issues and bring first C-ITS into being, as e.g. recently demonstrated by Audi presenting the 'traffic light online info service' [AUDI AG, 2014] in Las Vegas at the Consumer Electronics Show 2014. GEDDES statement of 1940 slowly becomes reality.

“The two, the car and the road, are both essential to the realization of automatic safety.
It is a job that must be done by motor-car manufacturers and road builders cooperatively.”
[GEDDES, 1940]

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List of Abbreviations

Abbreviation	Meaning
ADAS	advanced driver assistance systems
ARD	average required deceleration
C2C-CC	Car-to-Car Communication Consortium
CALM	communication access for land mobile
CAM	cooperative awareness message
CAS	collision avoidance systems
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
C-ITS	Cooperative Intelligent Transport System(s)
COR	correlation index
DAB	Digital Audio Broadcast
DeltaS	maximum relative speed
DENM	decentralized environmental notification message
DoT	Department of Transportation
DSRC	dedicated short range communication
DST	deceleration to safety time
DVF	displacement vector field
EC	European Commission
ET	encroachment time
ETSI	European Telecommunications Standards Institute
FGSV	Forschungsgesellschaft für Straßen- und Verkehrswesen
FOT	field operational test
GIDAS	German In-Depth Accident Study
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GT	gap time
HMI	human machine interface

Abbreviation	Meaning
I2I	infrastructure-to-infrastructure
I2V	infrastructure-to-vehicle
IAPE	initially attempted post encroachment time
ICT	Information and Communication Technologies
IDR	initial deceleration rate
IEEE	Institute of Electrical and Electronics Engineers
IR	infrared
IRIS	Intelligent Cooperative Intersection Safety
IRS	ITS roadside station according to ETSI terminology (former roadside unit (RSU) or roadside equipment (RSE) in the US)
ISO	International Organization for Standardization
ITS	Intelligent Transport System(s)
JDL	joint directors of laboratories
LDM	local dynamic map
MAE	mean absolute error
MAXE	maximum absolute error
MaxS	maximum speed
ms	millisecond
PET	post encroachment time
PSD	proportion of stopping distance
RDS/TMC	radio data system/traffic message channel
RFID	radio-frequency identification
RiLSA	Richtlinie für Lichtsignalanlagen (German Guidelines for Traffic Signals)
RMSE	root mean squared error
RP	resistance point
RT	reference track
s	second
SAE	U.S. Society of Automotive Engineers
TCT	traffic conflict technique
TET	time exposed time to collision

Abbreviation	Meaning
TIT	time integrated time to collision
TTC	time to collision
TTR	time to resistance point
UTC	universal time coordinated
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VANET	vehicular ad hoc network
VIS	vehicle ITS Station (former onboard unit (OBU))
VMS	variable message sign
WAVE	wireless access in vehicular environments
WLAN	wireless local area network

List of Indexes and Symbols

Index	Meaning
$(\cdot)_m$	column of a cell
$(\cdot)^d$	delay
$(\cdot)^{aw}$	driver awareness
$(\cdot)^{geo}$	geometric
$(\cdot)_{max}$	maximum
$(\cdot)_{min}$	minimum
$(\cdot)^{norm}$	normalized
$(\cdot)_t$	number of prediction time step
$(\cdot)^\perp$	orthogonal
$(\cdot)_k$	reference track
$(\cdot)^{req}$	required
$(\cdot)^{res}$	residual
$(\cdot)^r$	resistance point
$(\cdot)_n$	row of a cell
$(\cdot)_s$	segment of a reference track
$(\cdot)^{typ}$	typical
$(\cdot)_i$	vehicle

Symbol	Meaning
c	cell of a grid
d	distance
h	entry approach of intersection
$erf(\cdot)$	error function
Δt	length of prediction time step
l	length of vehicle
λ	line indicator
n	node of a reference track

Symbol	**Meaning**
tp	point in time the vehicle reaches the resistance point
z	position of moving object
T	prediction horizon in time
p	probability
r	radius of the earth
$\mathcal{H}$	set of overlapping reference tracks in a single intersection approach
$\mathcal{K}$	set of reference tracks
$\mathcal{I}$	set of vehicles
v	speed of moving object
ω	speed vector in relation to the polyline segment
η	standard deviation of the direction of moving object
σ	standard deviation of the position of moving object
b	status of turn signal
t	time
w	width of lane

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Annex

Detailed test results for IRIS

Test Case 1 - red light violation - green

Evaluation Sheet No: IRIS_Dortmund_DE_ 01
Test Number: 1

Test Case 1	Basic Settings					Technical Results							Technical Success Rate	remarks
run_id	actor	role	partner	speed	traffic light	Status Infra	Status Veh	Position	LDM	VANET	IRIS	HMI		
011_01	vehicle	violator	none	50	green	1	1	1	1	1	1	-	✓ 100.00%	no message issued
011_02	vehicle	violator	none	50	green	1	1	1	1	1	1	-	✓ 100.00%	no message issued
011_03	vehicle	violator	none	50	green	1	1	1	1	1	1	-	✓ 100.00%	no message issued
011_04	vehicle	violator	none	50	green	1	1	1	1	1	1	-	✓ 100.00%	no message issued
011_05	vehicle	violator	none	50	green	1	1	1	1	1	1	-	✓ 100.00%	no message issued
011_06	vehicle	violator	none	50	green	1	1	1	1	1	1	-	✓ 100.00%	no message issued
										IRIS Success	**100%**			

Test Case 2 - red light violation - red stop

Evaluation Sheet No: IRIS_Dortmund_DE_ 01
Test Number: 2

Test Case 2	Basic Settings						Technical Results							Technical	
run_id	actor	role	partner	speed	traffic light	stop_line	Status Infra	Status Veh	Position	LDM	VANET	IRIS	HMI	Success Rate	remarks
012_01	vehicle	violator	none	50	red	real	1	1	0	1	1	1	-	✓ 83.33%	no message issued, bad positioning (ca. 10 m to left, other direction)
012_02	vehicle	violator	none	50	red	real	1	1	1	1	1	1	-	✓ 100.00%	no message issued
012_03	vehicle	violator	none	50	red	real	1	1	1	1	1	1	-	✓ 100.00%	no message issued
012_04	vehicle	violator	none	50	red	real	1	1	1	1	1	1	-	✓ 100.00%	no message issued
012_05	vehicle	violator	none	50	red	real	1	1	1	1	1	1	-	✓ 100.00%	no message issued
012_06	vehicle	violator	none	50	red	real	1	1	1	1	1	1	-	✓ 100.00%	no message issued
										IRIS Success		100%			

Test Case 3 - red light violation - warning (unicast)

Evaluation Sheet No: IRIS_Dortmund_DE_ 01
Test Number: 3

Test Case 3	Basic Settings					Technical Results							Technical	Speed Reduction	Speed Reduction		Distance before
run_id	actor	role	partner	speed	traffic light	Status Infra	Status Veh	Position	LDM	VANET	IRIS	HMI	Success Rate	(4m/s²)	(8m/s²)	remarks	Stop Point
013_01	vehicle	violator	-	50	red	1	1	1	0.5	0.5	1	0	! 71.43%	-		no message unicast on HMI but generated by IRIS	
013_02	vehicle	violator	-	50	red	1	0	1	0.5	0.5	1	0	! 57.14%	-	-	no message unicast on HMI but generated by IRIS, SP1 crashed	
013_03	vehicle	violator	-	50	red	1	1	1	0.5	0.5	1	0	! 71.43%	↓ 8.29%	↘ 16.59%	message unicast on LDM	2
013_04	vehicle	violator	-	50	red	1	1	1	0.5	0.5	1	1	✓ 85.71%	↘ 49.77%	↑ 99.53%	message unicast on TUC tool	12
013_05	vehicle	violator	-	50	red	1	1	1	0.5	0.5	1	0	! 71.43%	-	-	no message unicast on HMI but generated by IRIS	
013_06	vehicle	violator	-	50	red	1	1	1	0.5	0.5	1	1	✓ 85.71%	↗ 58.06%	↑ 100.00%	message unicast on TUC tool	14
013_07	vehicle	violator	-	50	red	1	1	1	0.5	0.5	1	0	! 71.43%	↗ 70.50%	↑ 100.00%	message unicast on LDM	17
013_08	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↑ 82.94%	↑ 100.00%	message unicast on HMI	20
013_09	vehicle	violator	-	50	red	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message unicast on HMI but generated by IRIS	
013_10	vehicle	violator	-	50	red	0	1	1	1	1	0	0	! 57.14%	-	-	no message, no signal from traffic light	
013_11	vehicle	violator	-	50	red	1	1	1	1	1	1	0	✓ 85.71%	↗ 58.06%	↑ 100.00%	message unicast on log file	14
013_12	vehicle	violator	-	50	red	1	1	1	1	1	1	0	✓ 85.71%	↘ 41.47%	↑ 82.94%	message unicast on LDM	10
013_13	vehicle	violator	-	30	red	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message unicast but generated by IRIS	
013_14	vehicle	violator	-	30	red	0	1	1	1	1	0	0	! 57.14%	-	-	no message	
013_15	vehicle	violator	-	30	red	1	1	1	1	1	1	0	✓ 85.71%	↘ 57.60%	↑ 100.00%	message unicast on log file	5
013_16	vehicle	violator	-	30	red	1	1	1	1	1	1	0	✓ 85.71%	↘ 57.60%	↑ 100.00%	message unicast on log file	5
013_17	vehicle	violator	-	40	red	1	1	1	1	1	1	0	✓ 85.71%	↗ 71.28%	↑ 100.00%	message unicast on log file	11
013_18	vehicle	violator	-	40	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 71.28%	↑ 100.00%	message unicast on log file and HMI	11
013_19	vehicle	violator	-	40	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 64.80%	↑ 100.00%	message unicast on log file and HMI	10
013_20	vehicle	violator	-	60	red	1	1	1	1	1	1	1	✓ 100.00%	↑ 92.16%	↑ 100.00%	message unicast on log file and HMI	32
013_21	vehicle	violator	-	60	red	1	1	1	1	1	1	0	✓ 85.71%	↑ 89.28%	↑ 100.00%	message unicast on log file	31
013_22	vehicle	violator	-	70	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 74.06%	↑ 100.00%	message unicast on log file and HMI	35
013_23	vehicle	violator	-	70	red	1	1	1	1	1	1	0	✓ 85.71%	↗ 76.17%	↑ 100.00%	message unicast on log file	36
013_24	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 70.50%	↑ 100.00%	correct message received	17
013_25	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 74.65%	↑ 100.00%	correct message received	18
013_26	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 62.21%	↑ 100.00%	correct message received	15
013_27	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↑ 95.39%	↑ 100.00%	correct message received	23
013_28	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 62.21%	↑ 100.00%	correct message received	15
013_29	vehicle	violator	-	50	red	1	1	1	1	1	1	0	✓ 85.71%	↗ 58.06%	↑ 100.00%	correct message & also pedesrtrian warning received	14
013_30	vehicle	violator	-	50	red	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message	
013_31	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↑ 82.94%	↑ 100.00%	correct message received	20
013_32	vehicle	violator	-	50	red	1	1	1	1	1	0	0	! 71.43%	-	-	no message	
013_33	vehicle	violator	-	50	red	1	1	1	1	1	0	0	! 71.43%	-	-	no message	
013_34	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 74.65%	↑ 100.00%	correct message received	18
013_35	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 66.36%	↑ 100.00%	correct message received	16
013_36	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↗ 62.21%	↑ 100.00%	correct message received	15
013_37	vehicle	violator	-	50	red	1	1	1	1	1	1	1	✓ 100.00%	↑ 87.09%	↑ 100.00%	correct message received	21
013_38	vehicle	violator	-	50	red	0	0	1	1	1	0	0	✗ 42.86%	-	-	no message	
										IRIS Success	**85%**						

Test Case 4 - red light violation - warning (broadcast)

Evaluation Sheet No: IRIS_Dortmund_DE_ 02
Test Number: 1

Test Case 4	Basic Settings					Technical Results								
run_id	actor	role	partner	speed	traffic light	Status Infra	Status Veh	Position	LDM	VANET	IRIS	HMI	Technical Success Rate	remarks
021_01	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	1	✓ 100.00%	broadcast ok
021_02	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	1	✓ 100.00%	broadcast ok
021_03	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	1	✓ 100.00%	broadcast ok
021_04	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	1	✓ 100.00%	broadcast ok
021_05	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_06	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	1	✓ 100.00%	broadcast ok
021_07	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	1	✓ 100.00%	message broadcast on HMI
021_08	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_09	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_10	vehicle_2	endangered	vehicle_1	0	green	0	1	1	1	1	0	0	! 57.14%	no message
021_11	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_12	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_13	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_14	vehicle_2	endangered	vehicle_1	0	green	0	1	1	1	0	0	0	✗ 42.86%	no message, router crashed
021_15	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_16	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_17	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	message broadcast in log and IRIS
021_18	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_19	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_20	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_21	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_22	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
021_23	vehicle_2	endangered	vehicle_1	0	green	1	1	1	1	1	1	0	✓ 85.71%	no message on HMI but generated by IRIS
										IRIS Success	**91%**	6		

Test Case 5 - right turn - cyclist

Evaluation Sheet No: IRIS_Dortmund_DE_ 03
Test Number: 1

Test Case 5	Basic Settings					Technical Results							Technical Success Rate	Speed Reduction (4m/s²)	Speed Reduction (8m/s²)		Distance before Stop Point
run_id	actor	role	partner	speed	traffic light	Status Infra	Status Veh	Position	LDM	VANET	IRIS	HMI				remarks	
031_01	Daimler	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 34.56%	↘ 69.12%	message received	3
031_02	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
031_03	Daimler	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	↓ 23.04%	↓ 46.08%	only ldm, SP4 crashed	2
031_04	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
031_05	Daimler	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 34.56%	↘ 69.12%	message received	3
031_06	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
031_07	Daimler	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
031_08	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 57.60%	↑ 100.00%	message received	5
031_09	Daimler	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
031_10	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
031_11	Daimler	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 57.60%	↑ 100.00%	message received	5
031_12	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
031_13	TUC	violator	cyclist	30	green	0	1	1	1	1	0	1	! 71.43%	-	-	no message received	
031_14	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
031_15	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 57.60%	↑ 100.00%	message received	5
031_16	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_17	TUC	violator	cyclist	30	green	1	0	0	1	1	1	0	! 57.14%	-	-	no message received	
031_18	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_19	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_20	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 57.60%	↑ 100.00%	message received	5
031_21	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_22	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
031_23	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_24	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_25	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_26	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↗ 80.64%	↑ 100.00%	message received	7
031_27	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_28	TUC	violator	cyclist	30	green	0	1	1	1	1	0	1	! 71.43%	-	-	no message received	
031_29	TUC	violator	cyclist	30	green	0	1	1	1	1	0	1	! 71.43%	-	-	no message received	
031_30	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
031_31	TUC	violator	cyclist	30	green	1	1	1	1	1	1	0	✓ 85.71%	-	-	no message received	
031_32	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 57.60%	↑ 100.00%	message received	5
031_33	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
031_34	TUC	violator	cyclist	30	green	1	0	1	1	1	1	0	! 71.43%	-	-	no message received	
031_35	TUC	violator	cyclist	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
										IRIS Success	**91%**						

Test Case 6 - right turn - pedestrian

Evaluation Sheet No: IRIS_Dortmund_DE_ 03
Test Number: 2

Test Case 6	Basic Settings					Technical Results							Technical Success Rate	Speed Reduction (4m/s²)	Speed Reduction (8m/s²)		Distance before Stop Point
run_id	actor	role	partner	speed	traffic light	Status Infra	Status Veh	Position	LDM	VANET	IRIS	HMI				remarks	
032_01	Daimler	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
032_02	TUC	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
032_03	Daimler	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↓ 46.08%	↑ 92.16%	message received	4
032_04	TUC	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 57.60%	↑ 100.00%	message received	5
032_05	Daimler	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
032_06	TUC	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↘ 69.12%	↑ 100.00%	message received	6
032_07	Daimler	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 92.16%	↑ 100.00%	message received	8
032_08	TUC	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 100.00%	↑ 100.00%	message received	10
032_09	Daimler	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 100.00%	↑ 100.00%	message received	12
032_10	TUC	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 100.00%	↑ 100.00%	message received	14
032_11	TUC	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 100.00%	↑ 100.00%	message received	16
032_12	TUC	violator	pedestrian	30	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 100.00%	↑ 100.00%	message received	18
										IRIS Success	**100%**						

Test Case 7 - left turning - vehicle

Evaluation Sheet No: IRIS_Dortmund_DE_ 04
Test Number: 1

Test Case 7	Basic Settings					Technical Results							Technical	Speed Reduction	Speed Reduction		Distance before
run_id	actor	role	partner	speed	traffic lig	Status Infra	Status Veh	Position	LDM	VANET	IRIS	HMI	Success Rate	(4m/s²)	(8m/s²)	remarks	Stop Point
041_01	TUC	violator	TUC	25	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 99.53%	↑ 100.00%	shortly after stop line, unicast on HMI	6
041_02	Daimler	violator	Daimler	25	green	1	1	1	1	1	1	1	✓ 100.00%	↗ 82.94%	↑ 100.00%	shortly after stop line, unicast on HMI	5
041_03	TUC	violator	Conti	25	green	1	1	1	1	1	1	1	✓ 100.00%	↗ 82.94%	↑ 100.00%	shortly after stop line, unicast on HMI	5
041_04	Daimler	violator	TUC	25	green	1	1	1	1	1	1	1	✓ 100.00%	↑ 99.53%	↑ 100.00%	shortly after stop line, unicast on HMI	6
										IRIS Success	**100%**						